UNIVERSITY OF ALBERTA

SELECTION AND OPTIMIZATION OF COAGULANTS AND INVESTIGATION OF FLOCCULATION MIXING INTENSITY FOR DISSOLVED AIR FLOTATION TREATMENT OF ALGAE-LADEN WATERS

BY

KARINA BODO

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Selection and Optimization of Coagulants and Investigation of Flocculation Mixing Intensity for Dissolved Air Flotation Treatment of Algae-laden Waters** submitted by Karina A. M. Bodo in partial fulfilment of the requirements for the degree of **Master of Science** in **Environmental Science**.

Dr. D.W. Smith (Supervisor)

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Date: 24 May 96

ABSTRACT

The main goal of this research was to optimize certain parameters related to the performance of dissolved-air flotation (DAF) for the treatment of algae-laden waters. The specific objectives included to: 1) evaluate various coagulants to determine the optimum dose for effective DAF performance; 2) compare statistically the performance of the various coagulants; 3) investigate the effect of flocculation mixing intensity and flocculation time on the performance of DAF in a pilot plant; 4) investigate the effect of variations in flocculation mixing intensity on the DAF treatment of synthetic water spiked with *Chlorella vulgaris*; 5) investigate the effect of variations in flocculation mixing intensity on the DAF treatment of natural water spiked with *Chlorella vulgaris*; and 6) investigate the relationship between flocculation mixing intensity, particle size distribution and DAF performance.

Research results found that chemical treatment with coagulants is necessary for effective DAF treatment. Aluminum-based coagulants performed better than iron-based coagulants or organic polymers used as primary coagulants, in terms of percent reduction of dissolved organic carbon (DOC), chlorophyll-a, true colour, and turbidity. For both the synthetic water and natural water spiked with algae, treated water quality using the bench top apparatus improved up to an optimum "G" value of 60 s^{-1} to 70 s^{-1} with no additional improvement at higher values. A relationship was seen between particle size distribution and DAF performance, and

particle size distribution and flocculation mixing intensity. A relationship between DAF performance and flocculation mixing intensity was harder to determine since the particle size distribution changes over time during mixing.

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LIST OF ABBREVIATIONS

AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
DAF	Dissolved Air Flotation
DOC	Dissolve Organic Carbon
ECR	Eriochrome Cyanine R
EPM	Electrophoretic Mobility
IAWQ	International Association for Water Quality
TDS	Total Dissolved Solids
THM	Trihalomethane
USEPA	United States Environmental Protection Agency

1. INTRODUCTION

1.1 Background

This research was done in conjunction with a contract from the Town of St. Paul, Alberta. The source of raw water for St. Paul is Lac St. Cyr. Lac St. Cyr is a surface water source with low turbidity, high organics, and frequent seasonal algae blooms. The high, varying concentrations of algae cause problems for the coagulation/filtration/chlorination treatment system presently in place. The algae causes filter clogging and filter breakthrough. As the organics are not effectively removed with this treatment, high doses of chlorine are required for disinfection, which in turn causes taste and odour problems in the town. An investigation into new methods of treatment was initiated to solve this problem. Originally, preozonation in conjunction with dissolved air flotation (DAF) was suggested. Due to malfunction of the ozone generator, this was not possible. However, this gave the opportunity for a greater number of coagulant types to be tested and the optimum coagulant type and dose to be established. It also afforded the possibility of investigating the effect of coagulation mixing intensity on DAF performance, which is heavily debated in the literature.

1.2 Research Objectives

The overall objective of the study can be summarized as the selection and optimization of coagulants and investigation of flocculation mixing intensity for dissolved air flotation treatment of algae-laden waters. However, several specific objectives define the individual sections of the research.

1.2.1 Evaluation of Various Coagulants and Coagulant Doses

The initial stage of the project was carried out at the water treatment plant in St. Paul. The objectives were: 1) to evaluate the coagulants (alum, PASS, PACl, NIAD-1, Ferrifloc, Magnifloc 572, Magnifloc 577, and Chitosan) and coagulant doses in conjunction with DAF in terms of turbidity, true colour, dissolved organic carbon (DOC), and chlorophyll-a reduction, and residual aluminum, and 2) to determine the optimum coagulants and coagulant doses.

1.2.2 Statistical Evaluation of Certain Coagulants at Optimum Doses

A statistical analysis of the DAF performance of a selected few of the coagulants investigated in the first part of the project at their optimum doses was carried out. The DAF performance was evaluated in terms of turbidity, true colour, DOC, and chlorophyll-a reduction, and residual aluminum. This stage was undertaken at the water treatment plant at St. Paul using Lac St. Cyr water.

1.2.3 Pilot Plant Evaluation of Flocculation Mixing Intensity and Time

At the pilot plant in the water treatment plant in St. Paul it was possible to run a series of trials to investigate the effect of flocculation mixing intensity and flocculation time on the performance of DAF using the optimum coagulant and coagulant dose determined in the previous stages. DAF performance was measured in terms of turbidity, true colour, DOC, and chlorophyll-a reduction.

1.2.4 Evaluation of Flocculation Mixing Intensity Using Synthetic Water

Experiments were run with the objective of evaluating the effect of flocculation mixing intensity on the performance of DAF using synthetic water spiked with *Chlorella vulgaris,* a unicellular, green algae. The performance of DAF was measured in terms of turbidity and chlorophyll-a reduction, electrophoretic mobility (EPM), and particle number and size distribution. These experiments were run at the University of Alberta.

1.2.5 Evaluation of Flocculation Mixing Intensity Using Lac St. Cyr Water

The objective of this stage of the experiments was to determine whether the results observed in the last stage of the experiments would also be observed in natural water spiked with *Chlorella vulgaris.* Therefore the effect of flocculation mixing intensity on the performance of DAF was evaluated. The performance of DAF was measured in terms of turbidity, filtered UV absorbance at 254 nm, chlorophyll-a and DOC reduction, EPM, and particle number and size distribution. These experiments were carried out at the University of Alberta.

1.2.6 Investigation of Flocculation Mixing Intensity, Particle Size Distribution and DAF Performance

The purpose of this final stage of experiments was to investigate the relationship between flocculation mixing intensity, particle size distribution, and DAF performance. For example, can a relationship be seen between flocculation mixing intensity, particle size distribution, and DAF performance. DAF

performance was measured in terms of turbidity, chlorophyll-a reduction and particle number and size distribution. The experiments were done at the University of Alberta with synthetic water.

1.3 Limitations of Project

The optimization of coagulant type and dose in the first stages of the project are dependent on the characteristics of the raw water. It is important to recognize that optimization of coagulant type and dose is source-specific and therefore will not apply directly to any other water source or even the same water source under different conditions. The experiments involving spiked, synthetic water are replicable and therefore should have universal application.

This project did not investigate the effects of many parameters that have an effect on DAF. The greatest care was taken to fix parameters where possible. Where this was not practical, careful note was made of any change in parameter values.

2. LITERATURE REVIEW

2.1 Problems With Algae

Algae is commonly found in natural surface water reservoirs in Canada. In the right conditions, it is possible for algae blooms to occur which can cause problems for water treatment. An algae bloom is a period of explosive growth that occurs under favourable conditions of nutrients, sunlight, and heat. The term "algae" is usually used to describe phytoplankton in the size range of a few microns to a few millimetres (AWWARF, 1991). Various treatment problems associated with large concentrations of algae in the source water are described below.

2.1.1 Short Filtration Runs

Algae blooms are, by definition, the formation of large amounts of particulate organic matter. As this matter travels through the treatment system, it can clog the body of the filters or blanket the surface of the filters and cause premature filter breakthrough. The photosynthetic activity of algae can cause the water to become supersaturated with oxygen. Filter malfunction occurs when bubbles of oxygen are released into the filter from the supersaturated water.

2.1.2 Poor Coagulation and Flocculation

The photosynthetic activity of the algae can cause sudden pH changes in the water which may affect coagulation and flocculation processes. Some species of algae produce organic compounds that inhibit flocculation by complexing with metallic cations found in many coagulants. Algae have very low densities, which create difficulties in treatment by settling.

2.1.3 Formation of Trihalomethanes

The decomposition of algae is a prime source of humic and fulvic acids which are know to be trihalomethane (THM) precursors (Edzwald, et al., 1985; Stevens and Symons, 1980). Trihalomethanes are formed when these organics react with chlorine added for disinfection, and consist of several chemical species, including chloroform, bromodichloromethane, bromoform, and chlorodibromomethane. The first three listed have been classified by the USEPA as being probable or possible human carcinogens (Jasim, 1993). The potential to form THMs varies between algal species. The greatest THM formation occurs in the log phase of growth and with increasing temperatures, pH, chlorine dose and contact time (Wardlaw et al., 1991).

2.1.4 Taste, Odour and Toxins

Certain species of algae excrete metabolites that produce intense odour- and taste-causing molecules in very small quantities (Bernhardt, 1994). Other species of algae, especially blue-green algae, or cyanobacteria, produce water-soluble neuro- and hepatotoxins when they die and degrade. These toxins may be responsible for fish kills, and loss of livestock, and can be dangerous to humans (Kotak et al., 1993).

2.2 Dissolved-Air Flotation (DAF)

DAF has been used in water treatment for over 20 years in Europe and is the preferred method of clarification in countries such as England, Belgium, the Netherlands, and the Scandinavian countries (Edzwald et al., 1992). It has been shown to be effective for the treatment of waters containing low density particles such as algae, and on low turbidity, soft, highly coloured waters that produce light flocs. (Zabel, 1985; Heinanen, 1988; Edzwald and Malley, 1990; Janssens, 1991; Arora et al., 1994).

2.2.1 Overview of DAF

There are a number of variations of DAF systems (Pontius, 1990). The most commonly used variant is recycle-flow pressure flotation. In this method, a part of the clarified effluent is saturated under pressure with air. The saturated water is introduced into the bottom of the clarification tank via nozzles or needles, resulting in a reduction of pressure. As the pressure is reduced, small bubbles (10

to 120 μm in diameter) are formed. These bubbles float up through the water in the clarification tank and attach to and carry with them the particles that are to be removed. The combination of flocs and bubbles at the surface forms a sludge or float which can be continuously or intermittently removed by flooding or mechanical scraping. The treated water is filtered and chlorinated before entering the distribution system. A schematic diagram of a general recycle-flow pressure flotation system is shown in Fig. 2.2.1.

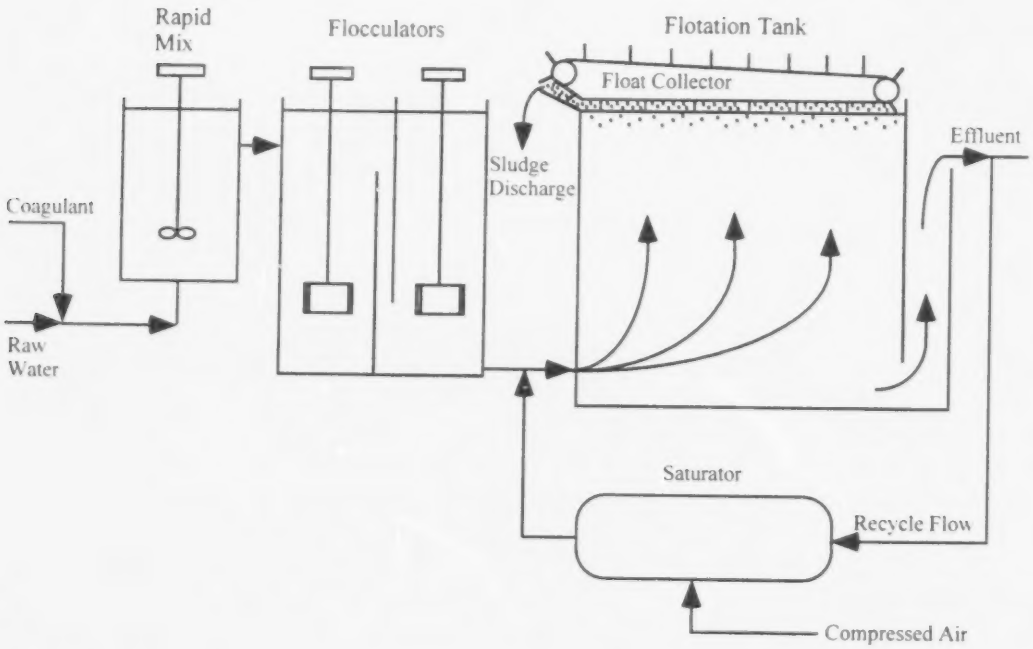


Fig. 2.2.1 Schematic Diagram of a General Recycle-Flow Pressure Flotation System (Adapted from Hyde et al., 1977; Viessman and Hammer, 1985; and Pontius, 1990.)

2.2.2 Advantages of DAF

Much literature has been written regarding the several advantages of DAF over some conventional treatments such as sedimentation. For instance, less time is required for flotation than sedimentation, so smaller tanks can be used, which translates into lower capital costs. Smaller flocs are required, which need a shorter flocculation time and smaller tank. Dosages of coagulants and flocculants are usually lower than for conventional treatment. DAF is very effective in removing low-density compounds that tend to settle slowly, and is therefore ideal for removing algae (Janssens, 1991). In removing low density particles efficiently, the filter runs of the plant are increased in length. Finally, the solids concentration of the sludge produced in DAF at 4 to 8% solids (Viessman and Hammer, 1990) is higher than that of sedimentation, which reduces the cost of sludge disposal (Edzwald and Wingler, 1990; Edzwald et al., 1992). Zabel (1985) found that DAF can operate at high surface loadings, which facilitates the use of small, shallow plants. The same study found that the DAF plant could be started up quickly, giving steady and good water quality within 45 minutes.

2.2.3 Parameters of Concern

There are several parameters that are crucial to the successful operation of the DAF system. These parameters include floc size, bubble size, amount of air introduced into the system, pH, coagulant type and dose, retention time, flocculation time and mixing intensity, and particle stability. Some of these parameters are discussed in more detail below.

2.2.3.1 Floc Size

Studies on floc size have determined that a floc size of 10 to 30 μm is the optimal size for DAF (Edzwald et al., 1992). Klute et al. (1994) found that higher flocculation mixing intensities ($G = 50\ s^{-1}$) produced a narrower floc size distribution concentrated around diameters of 30 μm, compared to the wider size distribution produced by lower G values ($G = 15\ s^{-1}$). Odegaard (1994) found that flocculation efficiency increases with increasing flocculation G to a maximum value ($G = 70\ s^{-1}$) and decreases above that value. The small, strong, high-density flocs produced by this mixing can better resist the high shear and turbulence at the outflow openings of the nozzles (Janssens, 1991; Bunker, et al., 1994). However, there is some discussion in the literature as to whether large or small flocs are optimal for DAF. Tambo (1990) stated that larger floc size and higher air bubble concentration increase the rate of flotation. Fukushi et al. (1994) explained that in a kinetic model, larger flocs in the range of 10 to 1000 μm are more effective in DAF as they have a higher collision efficiency and lower density. Using a different model, Malley and Edzwald (1991) and Edzwald and Malley (1990) disagree and state that pinpoint flocs (10 to 30 μm) are optimum for DAF.

Several advantages may be garnered if the floc size required for DAF is smaller than for conventional treatment (approx. 100 μm). For instance, a shorter flocculation time is required. Flocculation times of 5 to 20 minutes have been reported for pilot-plant and full scale studies (Heinanen, 1988; Janssens, 1991;

Malley and Edzwald, 1991; van Craenenbroek et al., 1993), compared to an average of 30 minutes for conventional treatment (Malley and Edzwald, 1991).

2.2.3.2 Bubble Size

In DAF, bubbles are released into the flotation tank by dissolving air under pressure into the recycle flow in a saturator. Common saturator pressures in pilot-plant studies are 350 to 585 kPa (Hyde et al., 1977; Edzwald and Wingler, 1990; Malley and Edzwald, 1991; Adkins and Harris, 1994). Recycle flows are commonly between 4 and 15% of the raw water flow (Edzwald et al., 1992; van Craenenbroek, 1993; Bunker et al., 1994; Johnson et al., 1994; Schmidt et al., 1994). The pressure is lowered to atmospheric pressure by releasing the water containing the dissolved air through needles or nozzles in the flotation tanks and numerous small bubbles are produced instantaneously. In DAF, small bubbles are optimal so they rise under laminar flow conditions and their motion can be described by Stoke's Law. Malley and Edzwald (1991) found that bubble diameters of 10 to 100 μm were the best size for efficient operation. Bubble diameters of 20 to 100 μm were found to be very effective in removing algae (Janssens, 1991).

2.2.3.3 Amount of Air

The amount of air added to a system is controlled mainly by the recycle ratio and the saturator pressure. Zabel (1985) found that the quantity of air required depends on the quantity of water to be treated, unless the concentration of suspended solids is very high (>1000 mg/L). The amount of air added to the system can be measured as the bubble volume concentration, the mass concentration of air, the number concentration of bubbles, or the recycle ratio (Edzwald, 1993a). Malley and Edzwald (1991) found that a bubble-volume concentration that is much greater than the particle-volume concentration is desirable to ensure many collision opportunities and to lower floc density. Common bubble-volume concentrations are in the range of 4600 ppm (Edzwald and Malley, 1990).

2.2.3.4 Particle-bubble Attachment Efficiency

Particle-bubble attachment efficiency is one of the most important parameters in DAF. Collisions between particles and bubbles occur as a two step process (Malley and Edzwald, 1991). Step one is the transport of the bubble to the particle surface. Step two is the attachment of the bubble to the particle. In order to get good particle-bubble attachment, the charge on the floc particles must be low. This is accomplished by chemical pre-treatment (coagulation/flocculation) prior to DAF.

There are several possible causes of stability between particles and bubbles (Edzwald et al., 1992). One such cause is the electric charge interaction between the particle and the bubble if they are similarly charged. Another cause is the hydrophilic effect caused by water bound to the surface of the bubble. Flotation requires destabilized, hydrophobic particles with low or no charge. This can be accomplished by chemical pre-treatment involving coagulation and flocculation similar to that done in conventional sedimentation and filtration. However, the flocs required for DAF are much smaller, as was mentioned previously.

2.3 Coagulation and Flocculation

As was shown in the previous section, coagulation and flocculation are vital to the efficient performance of DAF. Chemical pre-treatment is necessary to destabilize the particles in order that effective collisions between particles to form flocs and between bubble and flocs may occur. To understand the mechanisms of particle destabilization, it is necessary to take a closer look at the causes of colloidal particle stability and particle destabilization in water. Physical transport of particles in water is an important mechanism of flocculation. An understanding of the causes of physical transport is helpful in optimizing flocculation parameters.

2.3.1 Causes of Particle Stability

2.3.1.1 Electrostatic Stability

Algae in water generally have a negative charge. This charge is often produced by carbonyl and phenolic groups on cell surfaces. As the pH increases, the surface charge becomes more negative as the groups on the surface lose their H^+ ions. The concentration and reactivity of the surface groups depends on the growth phase and metabolic activity of the cell (Bernhardt and Clasen, 1994). The surface charge on the algae depends then on the pH of the solution, as well as the physical condition of the algae.

Since the alga particle is negatively charged, a cloud of positively charged ions is attracted around it. This concentration of positively charged ions then attracts a weaker, more diffuse layer of negative and positive ions. These two layers are called the diffuse electrical double layer. It is electrostatic repulsive interactions between the double layers of algal cells that is a factor in colloidal particle stability (Edzwald, 1993b). During effective chemical pre-treatment, the repulsive interaction between the double layers are weakened thereby allowing the increased particle-particle and, ultimately, particle-bubble contact that is essential for effective DAF treatment.

2.3.1.2 Hydrophilic Effects

When water is bound to a particle, the affinity of that particle for water will be increased and the likelihood of the colloids bonding together is slim. The water particles also form an effective liquid barrier to particle collisions (Montgomery, 1985).

2.3.1.3 Steric Stabilization

It is common for macromolecules such as large polymers to adsorb onto the cell surface of algae. When particles coated with these molecules collide, there can be repulsion by either compression or interpenetration of the adsorbed layers on the cell surface. With compression, two cells collide and the adsorbed layers are compressed, decreasing the volume available for the polymer molecules. The movement of the macromolecules is restricted and repulsion occurs between the molecules in that area. With interpenetration, the concentration of polymers in the collision region is increased. If the polymers are hydrophilic, they will prefer to react with the water phase rather than each other and repulsion will occur (AWWA, 1990).

2.3.2 Destabilization and Types of Coagulants

There are several types of coagulants available for chemical pre-treatment preceding DAF. While the goal of these coagulants is to destabilize particles, the mechanisms with which they work are varied. Below are some destabilization mechanisms and the coagulants that employ them as described in AWWA (1990).

2.3.2.1 Double-layer Compression

This mechanism affects the diffuse electrical double layer. High concentrations of cations and anions are added to the water, producing an increase in ionic strength and high concentrations of the counterions in the diffuse layer. As this occurs, the thickness of the double layer required to maintain neutrality is reduced and the range of repulsive interactions between particles is also reduced. Therefore, van der Waals forces can come into effect and the electrostatic barrier is reduced. Coagulants that employ this mechanism are inorganic salts such as alum, polyaluminum chloride, and ferric sulphate, to name a few.

2.3.2.2 Adsorption and charge neutralization

In this mechanism, the coagulant adsorbs to the particle and neutralizes the charge on the particle. The electrostatic forces are reduced and the particles are free to collide and agglomerate. Coagulants that use this mechanism are cationic polyelectrolytes, hydrolyzed aluminum ions, and ferric species.

2.3.2.3 Enmeshment in a Precipitate

If added in high enough concentration to water, metal salts such as alum and ferric sulphate will hydrolyze and precipitate a metal hydroxide. These precipitates can then enmesh and collide with the particles. Subsequent removal of the metal hydroxide flocs also removes the particles.

2.3.2.4 Interparticle Bridging

Synthetic and natural organic polymers have high molecular weights and many sites available to adsorb colloidal particles. When a polymer chain adsorbs more than one particle, the particles are effectively linked and provide a larger target for collision. If overdosing occurs, particles may become restabilized by steric stabilization.

2.3.3 Coagulant Dose

Different coagulants are found to have different optimum ranges depending on the characteristics of the raw water. For example, water treatment of the Thames River, London, England with DAF was investigated by Hyde et al. (1977). During periods of high turbidity and algae, the optimum ferric chloride dose varied from 0.5 to 15 mg/L and the optimum alum doses varied from 2 to 8 mg/L as Al. Van Craenenbroek et al. (1993) conducted a flotation jar test on a surface water source with occasional algae blooms and found that an optimum alum dose was 20 to 30 mg/L as Al at a pH of 6.5 to 7 at 20 °C. In this study it was also found that at temperatures around 5 °C, PACl (Polyaluminum hydroxychlorosulphate) provided better treated water quality and was less pH dependent. These studies show that the effectiveness and optimum range of the coagulants depends heavily on the characteristics of the raw water. Therefore, it is necessary to screen a variety of coagulants to find the optimum coagulant and dose for a particular water.

Care must be taken with coagulant dosing, however, as over-dosing can cause weaker flocs and breakdown of flocs at the point where the saturated water enters the flotation tank.

Seasonal algae blooms are common in many surface drinking water sources. These blooms cause problems in treatment in a number of ways. They are often the cause of shorter filtration runs and poor coagulation and flocculation. They can also cause potential aesthetic and health problems with the formation of THMs, taste and odour compounds and toxins. One method of treating algae-laden water is dissolved air flotation, which has been used outside North America for this purpose for many years. There are several advantages to DAF over some conventional treatments. For instance, DAF requires less time than sedimentation, so smaller tanks can be used. DAF is effective in removing low density particles which would otherwise settle out slowly. The solids concentration of the sludge is higher in DAF than conventional sedimentation, reducing the cost of sludge disposal. However, there are several parameters that are crucial to the successful operation of DAF treatment. Some of these parameters are floc size, bubble size, amount of air introduced into the system, particle-bubble attachment efficiency, coagulant type and dose and particle stability. Coagulation and flocculation are key to the success of DAF treatment. It is important to choose a coagulant whose mechanisms of action work most effectively in the source water and to determine the correct dose.

2.3.4 Flocculation Processes

In order for destabilized particles to aggregate, they must be brought into contact with one another. There are three physical transport processes that do this. They are Brownian diffusion, fluid shear, and differential settling (Pontius, 1990).

2.3.4.1 Brownian Diffusion

Particles in water are constantly moving in random directions. This is because they are constantly "jostled" by surrounding water molecules. The water molecules themselves move because of the thermal energy of the fluid. Brownian diffusion is also called perikinetic flocculation.

2.3.4.2 Fluid Shear

This transport mechanism promotes interparticle collisions as the particles follow the bulk motion of the water, caused by mixing. The mixing causes velocity gradients (G) to occur in the water, which can be thought of as change in velocity with distance (dv/dz). The units of G are reciprocal time (s^{-1}). Fluid shear is also called orthokinetic flocculation.

2.3.4.3 Differential Settling

Particles in water settle at different velocities depending on their size and density. Faster settling particles will overtake slower particles, resulting in collisions. Gravity and the settling velocity of the particles are the main factors controlling this transport mechanism.

2.3.4.4 Calculation of G

In the case of flocculation mixing, fluid shear is the most important particle transport mechanism (Pontius, 1990). The velocity gradient, G, has historically been used to determine the power required for mixing. It is a simply-calculated parameter that relates well to theories of particle collision frequency put forward by Smoluchowski in 1917. The mean velocity gradient can be calculated by equation 2.4.

$$G = (P/\mu V)^{1/2} \qquad \text{Eq. 2.3.1}$$

Where P = the power dissipated in water

V = volume of water in the reactor

μ = the absolute viscosity of the water

The power (and therefore the G) provided to the fluid depends on the speed, shape and size of the paddle, as well as the volume and shape of the mixing vessel.

3. METHODS

3.1 Experimental Stages

The experimental work was done both in the water treatment plant at St. Paul and at the University of Alberta Environmental Engineering Laboratory. Bench scale experiments were done at the University and both bench scale and pilot plant experiments were done in St. Paul. Experimental protocols are described in the following sections.

3.1.1 Evaluation of Various Coagulants and Coagulant Doses

Screening was done as a series of jar tests using a flotation jar testing apparatus (Aztec, Oxon, England) that had been transported from the University of Alberta Environmental Engineering Laboratory to the Town of St. Paul, Alberta water treatment plant. Coagulants were added at various dosages to the jars in each run, with the exception of a control jar to which no coagulant was added. Rapid mixing was carried out at 400 rpm (G value of 350 s^{-1}) for 2 minutes, followed by flocculation mixing at 60 rpm (G value of 30 s^{-1}) for 10 minutes. DAF was carried out with a recycle ratio of 8% (i.e. 80 mL of saturated water in 1000 mL of water to be treated) from a saturator pressure of 483 kPa. It is important to note that "recycle" is termed as such by convention although there is technically no recycle in the system. After 10 minutes of flotation, samples were taken from the

bottom of the jar. Samples were analyzed in-situ for pH, temperature, turbidity, true colour and aluminum residual (aluminum based coagulants only). Samples for dissolved organic carbon (DOC) and chlorophyll-a were filtered, and stored at 4 °C until analysis could be carried out at the University of Alberta. The pH of the raw water was not fixed in order to simulate conditions in the water treatment plant at St. Paul.

Comparison of effluent water quality was based on percent removal from the raw water of turbidity, true colour, chlorophyll-a, and DOC. Comparison to the raw water accounted for any temporal variations in Lac St. Cyr water quality during the study period. The coagulants tested and their properties are summarized in Table 3.1.1.

Table 3.1.1 Summary of coagulants used in screening tests

	Alum	STERNPAC (PACl)	PASS	NIAD-1
general name	Aluminum sulphate	Polyaluminum hydroxchlorosulphate	Polyaluminum silicate sulphate	Polyhydroxyaluminum chloride
molecular formula	$Al_2(SO_4)_3 \cdot 14.3H_2O$	$Al_m(OH)_n(SO_4)_kCl_{3m-n-2k}$	$[Al_a(OH)_b(SO_4)_c(SiO_2)_d]_n$	$[Al_2(OH)_{6-x}Cl_x \cdot yH_2O]_{15}$
molecular weight	594	NA	NA	NA
% as Al	6.2	7.74	8.7	NA
solids (% weight)	48.5	NA	34 (minimum)	30 to 60
bulk viscosity (cps)	17 @ 26.6 °C	4.0 @ 25 °C	17 @ 25 °C	NA
specific gravity	1.333	1.203	1.34	1.4

	Ferrifloc	Magnifloc 572	Magnifloc 577	Chitosan
general name	Ferric sulphate	Cationic polyacrylamide	Cationic polyacrylamide	Deacylated glycol chitin
molecular formula	$Fe_2(SO_4)_3 \cdot 9H_2O$	NA	NA	$[C_8H_{11}O_4N]_x$
molecular weight	562	approx. 30 K	75 to 100 K	approx. 10^6
% as Al	ND	ND	ND	ND
solids (% weight)	20	50	50	NA
bulk viscosity (cps)	NA	80 to 125	550 to 750	200 to 800
specific gravity	1.58	NA	NA	NA

NA = Not available
ND = Not determined due to analytical constraints
K = 1000

3.1.2 Statistical Evaluation of Certain Coagulants at Optimum Doses

From the results of the previous stage, five of the original eight coagulants were chosen for statistical analysis. Representatives were chosen from each major coagulant type, i.e. aluminum-based and iron-based coagulants, and organic polymers. The coagulants chosen were those that effected the best DAF performance based on the parameters analyzed at their optimum doses. Trials and replicates of the coagulants (PASS, NIAD-1, Ferifloc, Magnifloc 572, and Magnifloc 577) were performed at the optimum doses. Experimental protocol and parameters were identical to the previous stage. Results obtained from this trial were subjected to Student t-tests to determine whether there was any difference in the effluent quality among the coagulants. Each coagulant was also compared to the control jars which contained no coagulant, to determine whether the coagulant increased the effectiveness of DAF. Statistical tests were carried out for turbidity, true colour, chlorophyll-a, and DOC reduction. The coagulants were then ranked according to their performance.

3.1.3 Pilot Plant Evaluation of Flocculation Mixing Intensity and Time

Initially a 2^3 factorial design was planned using two coagulants that had performed the best in the statistical tests, and varying flocculation mixing intensity. The coagulants chosen were NIAD-1 and Ferifloc. When the Ferifloc was added

during the trial in the pilot plant, the effluent water quality was worse than the influent water quality, especially with regards to turbidity and colour. A new 2^2 factorial experiment was designed using only NIAD-1 and varying flocculation mixing intensity and time.

In each trial, the optimum dose of NIAD-1 was determined in jar tests before the plant was run, in order to simulate possible procedures in a full-scale plant. Bench scale tests were done with the same protocol as for the previous experiments. The optimum dose from the preliminary bench scale tests was determined by turbidity and true colour reduction. DAF performance in the pilot plant was measured in terms of turbidity, true colour, DOC, and chlorophyll-a reduction. High and low values for flocculation mixing intensity were 70 s^{-1} and 30 s^{-1}. Values for flocculation time were 12 minutes and 24 minutes. The experimental design is summarized in Tables 3.1.2 and 3.1.3 following Box et al. (1978).

Table 3.1.2 The High and Low Levels for the Factorial Design Factors

Variable	+	-
X1=Mixing Intensity,G	70	30
X2=Flocculation Time, t	24	12

Table 3.1.3 Factorial Design Matrix

Experiment #	X1	X2	G(s^{-1})	t (min.)
1	-	-	30	12
2	+	-	70	12
3	-	+	30	24
4	+	+	70	24

Pilot plant parameters are shown in Table 3.1.4. A schematic diagram of the pilot plant is shown in Figure 3.1.1.

Table 3.1.4 Pilot Plant Operational Parameters

Flocculation Time, t (min)	12	24
Flocculation Process:		
- Flocculation tank volume, m^3	0.608	0.608
- $Q_{Floc.}$(controlled by F#2) , m^3/h (L/min)	3 (50.6)	1.5 (25)
- Flocculation mixing intensity, G (s^{-1})	30 & 70	30 & 70
- Mixer RPM, N (rpm)	23 & 38	23 & 38
- NIAD-1 stock solution: (diluted 10 times)		
- % Al in stock solution	5.7 %	5.7%
- specific gravity	1.2	1.2
- NIAD-1 optimum dose, mg/L as Al	30 (from jar test)	30 (from jar test)
- NIAD-1 flow rate, mL/min	22	11
DAF Process:		
- DAF tank volume, m^3	0.518	0.518
- DAF detention time, min	22	22
- Q_{DAF} , m^3/hr (L/min)	1.4 (23.5)	1.4 (23.5)
- Recycle ratio, $R=Q_R/F_{loc.}$(%)	8	8
- Recycle flow rate, Q_R ,m^3/hr (L/min)	0.24 (4)	0.12 (2)
-$Q_{waste} = Q_{Floc} - Q_{DAF}$, m^3/hr (L/min) (controlled by F#3)	1.6 (26.7)	0.1 (1.7)
- Saturator pressure, kPa	490	490

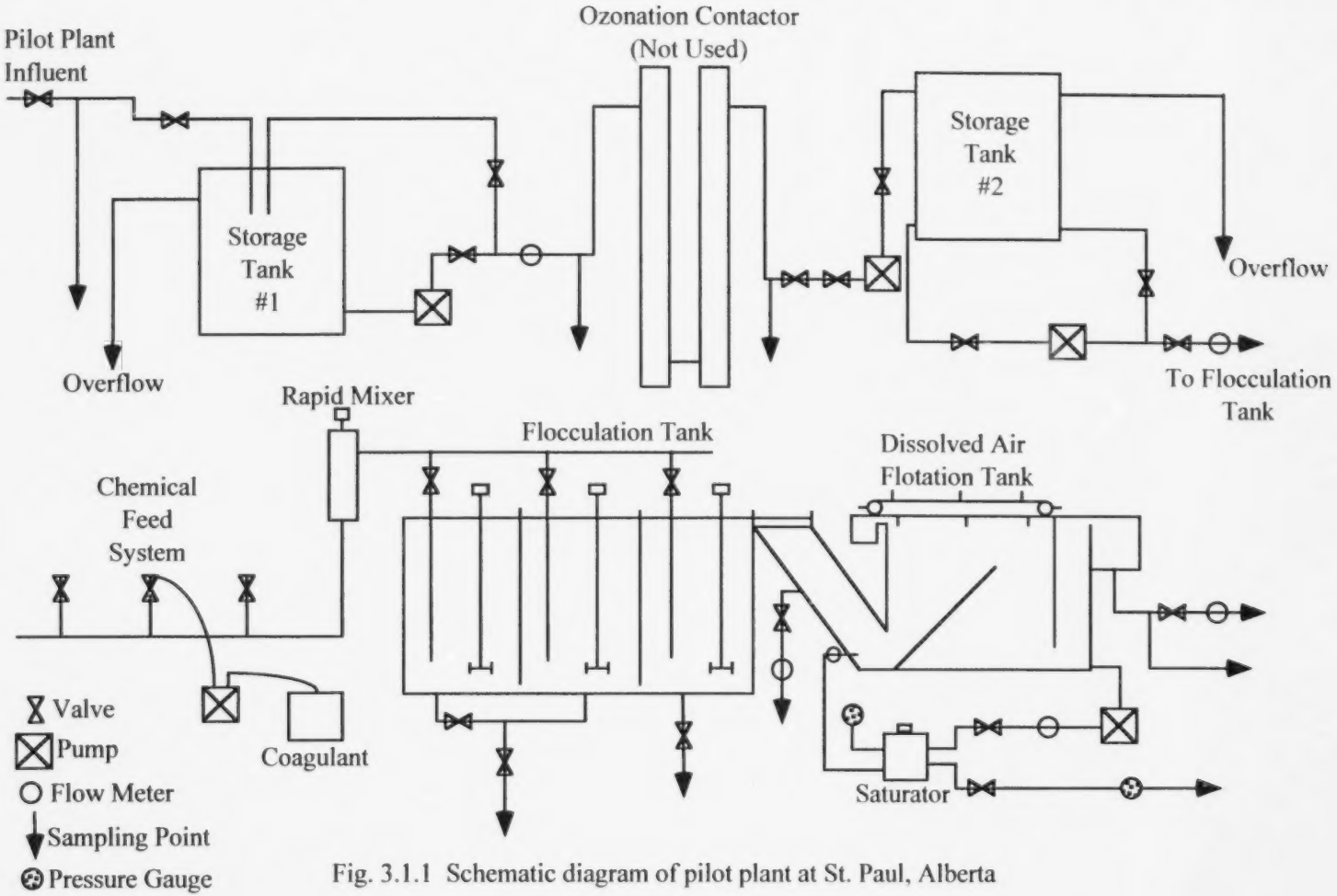


Fig. 3.1.1 Schematic diagram of pilot plant at St. Paul, Alberta

3.1.4 Evaluation of Flocculation Mixing Intensity Using Synthetic Water

Due to the variability of the natural water characteristics during the study period, it was difficult to establish a cause-effect relationship with particular parameters. In order to reduce this variability, synthetic water was used with the same inorganic characteristics as the natural water source. The synthetic water characteristics were: hardness of 120 mg/L as $CaCO_3$, ionic strength of 4.5×10^{-3} M, neutral pH, and no organic content. The water was spiked with algae in a concentration of approximately 10^5 cells/L to simulate a natural algae bloom (Bunker et al., 1994). The type of algae used was *Chlorella vulgaris*, a small, unicellular, non-motile green algae. It is commonly found in lakes in Northern Alberta and causes taste and odour problems in drinking water. PACl was chosen as the coagulant for its performance in the screening experiments, its known properties and its wide usage in full scale plants.

The optimum coagulant dose for the synthetic water was determined using the same method as described in Stage 1. The spiked synthetic water was first analyzed for pH, turbidity, chlorophyll-a, EPM, and particle size distribution and number. The spiked synthetic water was poured into the jars and the coagulant was added. The pH was adjusted to 5.5 which has been shown to be the optimum

pH value for the coagulation of *Chlorella vulgaris* (Bunker et al., 1994). Each set of tests consisted of a control (no coagulant added) and three replicates. The results were analyzed using ANOVA to determine any differences in DAF performance. The flocculation mixing intensities that were examined and the corresponding mixing speeds are shown in Table 3.1.5.

Table 3.1.5 Mixing Intensities and Corresponding RPM

Mixing Speed (RPM)	Mixing Intensity (s^{-1})
20	8
80	45
100	60
200	150
300	250
400	350

3.1.5 Evaluation of Flocculation Mixing Intensity Using Lac St. Cyr Water

The water for this section of the study was collected from the St. Paul water treatment plant in January and therefore contained very little algae. It was decided to spike the water with *Chlorella vulgaris* to simulate seasonal algae blooms. Lac St. Cyr water was collected in 20 L plastic containers and transported to the University of Alberta where it was stored in the dark at 4 °C and

used within a week of collection.

The spiked raw water was measured for pH, turbidity, filtered UV absorbance at 254 nm, chlorophyll-a, DOC, EPM, particle concentration and particle size distribution. First the optimum PACl dose was determined for the spiked natural water. This was done in a similar way to the previous stage of the experiments except that the pH was not adjusted to 5.5. Once the optimum dose was determined it was possible to proceed with the next part of this experiment.

Similar DAF procedures were used as in the synthetic water experiment except that only three mixing intensities were used. Three replicates were run for each of the three mixing intensities. No control was used as the variable being tested was mixing intensity and not coagulant type or dose. The mixing speeds used were 60, 100 and 300 rpm which correspond to mixing intensities of 30, 60 and 250 s^{-1}, respectively. Samples were analyzed for % reduction in turbidity, chlorophyll-a, filtered UV absorbance at 254 nm, DOC, particle concentration and particle size distribution.

3.1.6 Investigation of Flocculation Mixing Intensity, Particle Size Distribution and DAF Performance.

The greatest challenge in this stage of the experiments was to analyze the floc size distribution without breaking up the flocs. Special care was taken to prevent floc break-up during handling of the sample. Samples were taken from the middle of two of the four jars at times of 0 minutes (before flocculation mixing), and at 1 minute, 3 minutes, 5 minutes, 7 minutes, 9 minutes, and 10 minutes after the start of flocculation mixing. Samples to determine DAF performance were taken from the other two jars. DAF performance was measured as turbidity, and chlorophyll-a reduction and particle number and size distribution. All jars were subjected to the same conditions. Rapid mix speed, flocculation time, recycle ratio, and flotation time were the same as in the previous experiments. The flocculation mixing intensities that were examined were 60 rpm, 100 rpm, and 300 rpm, which correspond to G values of 30 s^{-1}, 60 s^{-1}, and 250 s^{-1}, respectively. Special care was taken in the handling of the particle size distribution samples. After a certain time lag due to the time restrictions of the experimental procedure, the samples were carefully transferred from the jars to a 100 mL volumetric flask that was then filled up to the mark with 0.6% Isotone solution after Bonner (1985). This solution increased the viscosity of the mixture, reducing floc break-up in the particle counter and reducing flocculation by Brownian motion (Bonner,

1985). The diluted samples were then mixed using a B&B SA-12 Motor Speed Control mixer at 6 rpm following the method outlined by Lawler et al. (1983). After mixing, the samples were analyzed using the particle counter (Hiac/Royco 8000, Montreal, Canada).

3.2 Explanation of Parameters

Various parameters were used to determine the performance of DAF treatment. These parameters are often surrogates for various parameters of water quality.

3.2.1 Chlorophyll-a

Chlorophyll-a is a photosynthetic pigment that is often used to measure the amount of phytoplankton biomass. Results in this study are presented as percent reduction of chlorophyll-a which may be read as reduction of algal biomass. This can be misleading, however, because different species of algae have different chlorophyll-a concentrations. This applies mainly to the experiments where natural raw water was used. For this reason, turbidity and particle number and size distribution were also measured.

3.2.2 Turbidity

Turbidity is caused by suspended matter, dissolved organic compounds, plankton, and other microscopic organisms. It is a measure of how much light is scattered or absorbed by the sample instead of passing through. Turbidity is an important parameter in water treatment as the turbidity affects the length of filter runs and the amount of chlorination required among other factors. In this research, turbidity was used mainly as an indication of the amount of suspended matter in the samples.

3.2.3 True Colour

True colour is the term used for the colour of the water after all suspended particles have been removed. Suspended matter can be removed by filtration or centrifugation. The remaining colour is usually caused by the presence of metallic ions, humus and peat materials, and industrial wastes. In this study, the suspended particulates were removed by filtration and the remaining colour was viewed as a measure of dissolved organic compounds and natural metallic ions. As discussed, true colour was measured using a Milton Roy Spectronic 601 as UV absorbance at 254 nm and a Hach DR/2000 spectrophotometer.

3.2.4 DOC

Total organic carbon is a measure of all the organic carbon present in a sample. It is measured by converting the organic carbon in the sample to carbon dioxide. Dissolved organic carbon is a similar measurement, but the samples are filtered to eliminate all suspended particulates. It is therefore a good measurement of all dissolved organic compounds, including those that do not cause colour.

3.2.5 EPM

Electrophoretic mobility is a measure of the charge on a particle. The charge on a particle is crucial to particle destabilization. By directly measuring the charge on a particle, EPM can provide a good indication of the optimum dose of a coagulant. It is often difficult to measure EPM on natural waters if there are mobile microscopic organisms present.

3.2.6 Particle Number and Size Distribution

This parameter is used in conjunction with chlorophyll-a to determine the number of algae cells left in the sample. The sizes of the channels on the particle counter are variable and different size distributions can be investigated. In the experiments where the samples were spiked with algae, the number of algae could be seen in the channels of sizes approximately 5 μm. The particle size distribution

is also useful in examining changes in floc size during flocculation. Particle size has also been used as an indicator of water treatment plant performance, such as when the filters are not operating properly. This is very useful information since filtration is the primary method for removal of *Giardia* and *Cryptosporidium* (LeChevalier and Norton, 1992).

3.2.7 Aluminum Residual

Aluminum-based coagulants leave a free aluminum residual in the treated water. The amount of free aluminum depends on the dose, pH, and type of coagulant. Lower aluminum residuals are favoured because of the possible, but as yet unproved, link between aluminum in drinking water and certain diseases, particularly Alzheimer's disease (Health Canada, 1995). Currently there is no governmentally controlled upper limit for free aluminum concentrations in drinking water. Health Canada is presently developing guidelines for free aluminum concentrations in treated drinking water (Health Canada, 1995) and therefore, this parameter was considered important.

3.3 Analytical Techniques and Solutions

Many analytical techniques and solutions were used in this research. The following is a detailed account of the main analytical procedures and methods of solution preparation mentioned above.

3.3.1 Aluminum Residual Determination

The method used to determine aluminum concentration was the Eriochrome Cyanine R (ECR) method (Hach Company, Loveland, Colorado). It uses a pre-programmed Hach DR/2000 spectrophotometer with pre-packaged reagents. In this method, ECR combines with aluminum to produce an orange-red colour. The intensity of colour is proportional to the concentration of free aluminum in the sample. The method is outlined below. This method was found to have a standard deviation of 0.004 mg/L Al. Fluoride has a strong interference effect with this method (APHA, 1992), therefore it is important to determine the concentration of fluoride in the water and adjust the results accordingly. A graph showing the aluminum/fluoride interference is shown in Figure 3.3.1.

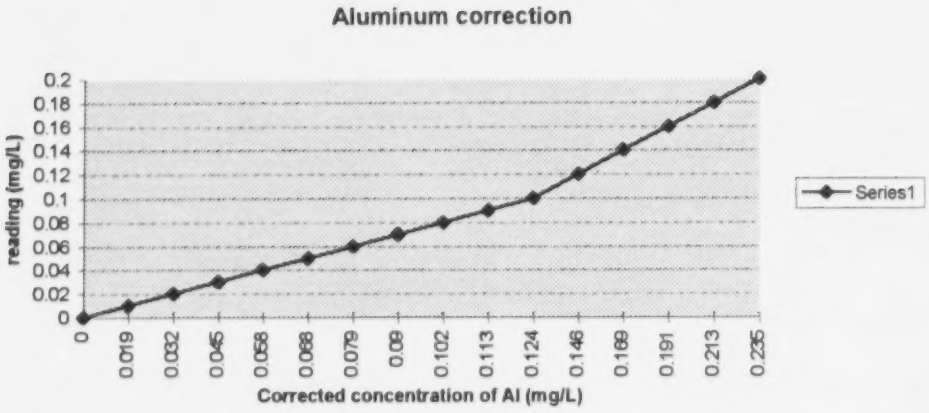


Fig. 3.3.1 Aluminum concentration corrected for fluoride interference (Hach DR/2000 spectrophotometer manual)

3.3.2 Preparation of Chitosan

The chitosan solution for coagulation was prepared according to the method described in Kawamura, 1991.

2.0 g of dry chitosan (deacylated glycol chitin, Sigma Chemicals) was dispersed in 100 mL of water. 100 mL of 2% acetic acid was added and the mixture was stirred until all the chitosan was dissolved (about 2 hours). The mixture was stored in a washed plastic bottle until used.

3.3.3 Chlorophyll-a Analysis

This protocol was based on Standard Methods 10200H (APHA, 1992). The extraction solvent used was 95% ethanol.

3.3.3.1 Sampling Procedure

A well-mixed volume of the sample was vacuum-filtered into a clean filtration funnel and the particulate matter was collected on a 47 mm diameter Whatman GF/C glass fibre filter. The volume of the filtered sample was recorded. Generally, 250 to 500 mL of sample was filtered. If processing of the samples was delayed, the samples were kept at 4 °C in opaque bottles or glass bottles wrapped in aluminum foil to protect them from exposure to the light.

Approximately 2 mL of 1% magnesium carbonate solution was added when the last 50 mL of sample passed through the filter to help buffer the sample against degradation. It was very important that the chlorophyll samples did not come into contact with acid during the preparation, as acid will degrade chlorophyll. Gloves were used during filtering. The filter paper was removed from the filter funnel with clean forceps, folded, and inserted into a clean, numbered 25 x 150 mm screw top test tube. The filters were stored in the dark and frozen to -20°C until extraction and analysis could be done.

3.3.3.2 Extraction Procedure

The work with chlorophyll extracts was conducted in subdued light to avoid degradation. Using an automatic pipette, 25 mL of 95% ethanol

was added slowly to the tube containing the filter. The tube was capped and shaken well until the filter paper was completely broken up. The samples were then placed in a dark freezer for sub-zero extraction at -5 °C to -15 °C for 24 hr.

3.3.3.3 Calibration of Fluorometer

One mg of pure chlorophyll-a from spinach (Sigma Chemicals) was dissolved in 100 mL of 95% ethanol (conc. ~ 10,000 μg/L). The measurement of the actual chlorophyll-a concentration was carried out using a Milton Roy Spectronic 601 spectrophotometer. The absorbance of the solution was measured at 648, 650, 664, 666, and 750 nm. These measurements were repeated several times and the average values taken. The absorbance at 649 nm was calculated by taking the average of the absorbances at 648 and 650 nm. Similarly, the absorbance at 665 nm was calculated by taking the average of the absorbances at 664 and 666 nm. The chlorophyll-a concentration was then calculated using the following formula:

$$Ca = 13.70\,(OD_{665} - OD_{750}) - 5.76\,(OD_{649} - OD_{750}) \quad \text{Eq. 3.3.1}$$

Where:

Ca = concentration of chlorophyll-a in the stock solution (in μg/mL),

OD_{665} = absorbance at 665 nm,

OD_{649} = absorbance at 649 nm,

OD_{750} = absorbance at 750 nm.

The concentration of chlorophyll-a was in μg/mL so it was necessary to multiply the value by 1000 to convert it to μg/L.

From this stock solution, 100 mL each of 2 μg/L, 6 μg/L, 20 μg/L and 60 μg/L were prepared. The following calibration factors were calculated using a Turner fluorometer model 111. For the sensitivity setting (sliding window orifice) 1X, the fluorometer reading (R_{1X}) was measured for the 2 μg/L standard and the calibration factor (F_{1X}) was calculated as follows:

$$F_{1X} = Ca / R_{1X} = 2\ \mu g/L / R_{1X} \qquad \text{Eq. 3.3.2}$$

The reading for the 6 μg/L standard (R_{3X}) was taken using the 3X sensitivity setting and the calibration factor (F_{3X}) was calculated as:

$$F_{3X} = 6\ \mu g/L / R_{3X} \qquad \text{Eq. 3.3.3}$$

The same procedure was followed for the 20 μg/L standard and the 10X sensitivity setting and the 60 μg/L standard and the 30X calibration setting. The calibration factors for the 10X and the 30X settings, respectively are:

$$F_{10X} = 20\ \mu g/L / R_{10X} \qquad \text{Eq. 3.3.4}$$

and

$$F_{30X} = 60\ \mu g/L / R_{30X}. \qquad \text{Eq. 3.3.5}$$

3.3.3.4 Fluorometric Determination of Chlorophyll-a Concentration in Unknown Sample

The samples were warmed up to room temperature in darkness and clarified by filtering through a Reeve Angle, 185-mm diameter folded filter before measuring the fluorescence. Readings were taken with each sample at the sensitivity level that gave a mid-scale reading. The concentration of the unknown sample was calculated by multiplying the reading obtained by the calibration factor for the sensitivity level at which the reading was taken.

3.3.4 True Colour Analysis

The analysis at the water treatment plant in St. Paul was done using a spectrophotometer (DR/2000, Hach Company, Loveland, Colorado). The instrument was set at a wavelength of 254 nm. Samples were filtered through 0.45 μm glass filters and 5 mL of phosphate buffer was added. The instrument was zeroed and the sample was analyzed by taking an average of several readings. The instrument was re-zeroed every few samples.

Analysis for true colour done at the University of Alberta was performed on a Milton Roy Spectronic 601 spectrophotometer. Samples were filtered through a 0.45 μm filter and adjusted to pH 7.0 using 0.05 M phosphate buffer. They were then poured into a 10 mm quartz cell and the absorbance at 254 nm was measured.

3.3.5 Electrophoretic Mobility (EPM) Measurements

Electrophoretic mobility for colloidal particles and algae was measured by using microelectophoresis apparatus (Mark II, Mono Research Laboratories, Missisauga, Ontario) and a rectangular flat cell.

3.3.5.1 System Calibration

Prior to the initial start up of EPM measurements, the system was calibrated according to directions in the manual provided with the instrument.

The length of the squares of the graticule was measured to ensure accurate calculations of EPM. This was done by observing a stage micrometer through the eyepiece. A stage micrometer is a slide engraved with 1 mm divided into 100 equal parts. Therefore it is possible to measure how many μm the squares are. This measurement was be done in air and in water.

3.3.5.2 System Operation and Maintenance

The sample was poured into the cell and the electrodes were inserted. The lens was focused on the area just behind the front panel of the cell. The voltage was turned on and increased until the particles in the sample cell moved at a reasonable rate. The time for a particle to travel from one side of a square in the eyepiece graticule to another was measured using a manually-operated timer. This was repeated for several particles of different sizes to give an average value (usually five to 10 particles). The voltage was reversed and the procedure was

repeated. From the voltage, speed and direction of the particle, the EPM of the particles in the solution could be calculated from the following equation:

$$EPM = v/F.S. \qquad \text{Eq. 3.3.6}$$

Where: EPM = electrophoretic mobility ({μm*cm}/{volt*s})

v = velocity of the particle (μm/s)

F.S. = Field strength (volts/cm)

3.3.6 Preparation of Electrolyte Solution: Isotone (0.6%)

The compounds used in the preparation of the Isotone solution are given in Table 3.3.1.

Table 3.3.1. Components of 0.6 % Isotone Solution

Compound	g/L
NaCl	6
Sodium azide	1
Polyvinylpyrrolidone-PVP-40T (Sigma)	35
$Na_2HPO_4 \cdot 12H_2O$	0.32
$NaH_2PO_4 \cdot H_2O$	0.04
NaOH	0.04

The solution was prepared as follows (Bonner, 1985):

1. The first two ingredients were added to 1 litre of deionized water and stirred magnetically on very low heat until all the ingredients had been added.

2. While stirring on low heat, the polyvinylpyrrolidone was added very slowly. It took 45 minutes to one hour to add this compound.

3. When the polyvinylpyrrolidone had dissolved completely, the remaining ingredients were added and stirred until dissolved.

4. The solution was filtered through a 0.2 μm filter and stored in deionized, rinsed containers.

3.3.7 Statistical Analysis

3.3.7.1 t-tests

The purpose of t-tests is to test if there is any difference between certain treatments. The t-tests work on the principle of hypothesis testing. A null hypothesis is chosen with an alternate hypothesis following from the null hypothesis. The null hypothesis is the statement that will be rejected or not rejected depending on the outcome of the statistics. An example of a null and an alternative hypothesis as well as the calculations used are given in Table 3.3.2. It is also necessary to establish the degree of certainty of the calculation. All the t-tests were tested at the 0.05 and 0.01 level of certainty. This means that we are respectively 95% and 99% certain that the conclusion ascertained by the statistics is the correct one. The level of certainty determines the critical t which is read

from a standard statistical table and compared to the calculated t. The relationship between the critical t and calculated t determines whether or not the null hypothesis is rejected.

A t-test can only be used to test one pair of treatments at a time, however, a series of t-tests can provide a comprehensive view of the difference and similarities among a set of treatments. For instance, a series of t-tests was used to determine the relative effectiveness of the different coagulants in the screening process. Initially, the performance of each of the coagulants was compared with the control to determine whether the addition of coagulant had an effect. Then each coagulant was in turn compared with all the other coagulants. The t-test assumes that data are normally distributed.

Table 3.2 Null and Alternative Hypothesis Used for the t-Test

Null Hypothesis Ho: $\mu 1 = \mu 2$; there is no significant difference between the treated waters

Alternative Hypothesis Ha: $\mu 1$ does not equal $\mu 2$; there is a significant difference between the treated waters

test statistic: t-test

degrees of freedom (ν) : (n1+n2)-2

critical values: α=0.05
α=0.01

Decision rule:
Reject Ho If $t_{calc} > t_{\alpha/2}$ or $< -t_{\alpha/2}$,

$$t_{calc} = ((x_1 - x_2) - (\mu_1 - \mu_2)) / (S_p(1/n_1 + 1/n_2)^{1/2})$$

$$S_p^2 = ((n_1 - 1)s_1 + (n_2 - 1)s_2) / (n_1 + n_2 - 2)$$

Explanation of variables

n_1 = number of replicates for coagulant#1
n_2 = number of replicates for coagulant#2
ν = degrees of freedom
s_1 = standard deviation for coagulant #1 "parameter" % reduction
s_2 = standard deviation for coagulant#2 "parameter" %reduction
x_1 = average of the "parameter" % reduction for coagulant #1
x_2 = average of the"parameter" % reduction for coagulant #2
t_{crit} = critical statistic
t_{calc} = calculated statistic
μ_1 = the mean value of % reduction of "parameter", such as DOC % reduction, for coagulant #1
μ_2 = the mean value of % reduction of "parameter", such as DOC % reduction, for coagulant #2

3.3.7.2 ANOVA

ANOVA stands for "Analysis of Variance". It is a statistical test to determine whether the variation between treatments is larger then the variations within the treatments. In other words, it is a tool to determine whether there is a difference among a set of treatments. The ANOVA is best described by means of the table below.

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F ratio
Between groups	2	0.0046	0.0023	6.3030
Within groups	6	0.0022	0.0004	
Total	8	0.0068		

The F ratio is the ratio of the mean square between groups over the mean square within groups. The F ratio is the calculated statistic which must be compared to the critical statistic. The critical F is determined from standard statistical tables and depends on the degree of certainty. In these experiments, the level of certainty or significance was 0.05, so there is a 95% certainty that the results of the statistics are correct. If it was determined that there was a difference among the treatments, then post-hoc tests were done to determine between which groups were the differences. Various post hoc tests, such as the Tukey-HSD test were used. ANOVA analysis assumes that data are normally distributed, but is robust in this respect.

3.3.8 Dissolved Organic Carbon (DOC) Analysis

Glass bottles (500 mL) with Teflon-lined caps were used for sample collection as per Standard Methods 5310C (APHA, 1992). The samples were preserved by acidification to pH 2 with HNO_3 and stored in the dark at 4°C. Prior to analysis, DOC samples were filtered through 0.45 μm filters and all samples were purged with prepurified oxygen for approximately 15 minutes to remove most CO_2. Analysis was performed with a Dohrman DC-80 total organic analyzer which operates on the principle of persulfate promoted oxidation followed by infrared detection of the resulting carbon dioxide. Samples were analyzed for non-purgable organic carbon which represents the DOC. Fresh standards were prepared weekly using potassium hydrogen phthalate to standardize total carbon analysis and sodium carbonate for inorganic carbon analysis. For each sample, three replicates were obtained and averaged.

3.3.9 Turbidity Analysis

Dissolved air flotation (DAF) samples from the jar tests were collected directly from the bottom port of the DAF jar into a 125 mL Erlenmeyer flask and transferred to the turbidimeter cuvette for analysis. Turbidity measurements were made using a Hach Turbidity Meter Model 2100A.

3.3.10 Synthetic Water

The compounds in Table 3.3.3 were dissolved in Milli-Q water to give synthetic water with the characteristics listed in Table 3.3.4.

Table 3.3.3 Components of Synthetic Water

Compound	g/L
NaHCO3	0.0840
CaCl2	0.1332
NaCl	0.2633

Table 3.3.4 Characteristics of Synthetic Water

Inorganic Component	Chemical Compound	Concentration
Alkalinity and buffer	$NaHCO_3$	10^{-3} M
Calcium hardness	$CaCl_2$	1.2×10^{-3} M (120 mg/L as $CaCO_3$)
Ionic strength (TDS = 180 mg/L)	NaCl	4.5×10^{-3} M
pH (neutral)	HCl or NaOH	1 N

3.3.11 pH

pH was determined using a Fisher Accumet pH meter model 805 MP. The meter was calibrated daily with pH 4.00 and 10.00 buffers and corrected for temperature.

3.3.12 Algae Cultures

Cultures of *Chlorella vulgaris* were grown in the laboratory at the University of Alberta. The *Chlorella sp.* was ordered from Sigma Chemical Company. A sample of algae was transferred using sterile methods into 60 mL of algal growth medium in a 125 Erlenmeyer flask that had just been autoclaved for 20 minutes at 120 °C. The algal growth medium was made in the lab following work performed by Edzwald and Malley (1989). The constituents of the growth medium are listed in Table 3.2.5. The cultures were shaken continuously and maintained at room temperature (approx. 22°C). The cultures were illuminated with at least 77.5 mEinstein/m^2 (600 foot candles) of fluorescent light at all times. Algal growth phase was monitored using a HIAC/ROYCO particle counter. The log growth phase was used for this research following the work done by Edzwald and Malley (1989). Seven to ten days were usually required for the cells to reach log growth in sufficiently high concentrations for use as a stock solution for spiking.

Table 3.3.5 Components of Algae Nutrient Solution

Chemical Component	Stock Concentration	mL Stock/ L medium
$CaCl_2 \cdot 2H_2O$	1.25 g/500 mL	10
$MgSO_4 \cdot 7H_2O$	3.75 g/500 mL	10
K_2HPO_4	3.75 g/500 mL	10
KH_2PO_4	8.75 g/500 mL	10
$NaNO_3$	12.5 g/500 mL	10
NaCl	1.25 g/500 mL	10
Na_2EDTA + KOH	10 g/L 6.2 g/L	1
H_3BO_3	5.75 g/500 mL	0.7
$FeSO_4 \cdot 7H_2O$ + H_2SO_4	4.98 g/L 1 mL/L	1
Trace Metal Mix		1
$CuSO_4 \cdot 5H_2O$	0.079 g/L	
$ZnSO_4 \cdot 7H_2O$	0.222 g/L	
$CoCl_2 \cdot 6H_2O$	0.0494 g/L	
$MnCl_2 \cdot 4H_2O$	1.81 g/L	
$Na_2MoO_4 \cdot 2H_2O$	0.390 g/L	
H_3BO_3	2.86 g/L	

3.3.13 Particle Number and Size Distribution

Particle number and size distribution was measured using an eight channel HIAC/ROYCO Model 8000A particle counter. Samples were measured at a flow rate of 0.42 mL sample per second. Samples were diluted if the particle count was predicted to exceed 18000 particles, the maximum number that the instrument can handle at one time. The instrument was flushed with Milli-Q water daily before beginning sampling, between each sample, and after all samples were analyzed. A background count of particles in the dilution water was taken for all samples and

subtracted from the count by the instrument. At least three replicates of each sample were done and the final data is an average of these replicates. Calibration of the particle counter was done initially to determine the instrument response to particles of known size. The flow rate of the sensor was determined to be 0.42 mL/s. Solutions of four different sizes of spheres in clean dilution water were made up in known concentrations of about 25% of the sensor maximum. These solutions were run through the instrument one at a time. The voltage reading at the median of the particle size distribution was determined. This voltage reading determined the threshold setting for particles of the size of the calibration spheres.

3.3.14 DAF Jar Tester Procedure

The components of the DAF jar tester included a compressed air cylinder, pressurization tank (saturator), and four coagulation-flocculation -flotation jars which were made of acrylic and had a maximum capacity of 1400 mL. The unit had a series of solenoid valves and recycle timers which allowed control of the flow of the air-saturated liquid from the saturator to the jars. Each jar had a retractable paddle mixer which was connected to a single speed control that could be operated at 20, 30, 40, 50, 60, 80, 100, 200, 300, or 400 rpm. The velocity gradient for the paddle mixers was determined and is outlined in the next section.

Experiments were conducted at room temperature (20 to 25 °C). Air-saturated water was made by placing 4 L of water into the saturator and increasing the pressure inside the saturator to 483 kPa (70 psi). The saturator was allowed to

stand for 10 minutes and was shaken three or four times during this period to ensure complete dissolution of the air. Before adding raw water, the lines between the saturator and the flotation jars were purged by initiating two recycle sequences. The jars were drained of liquid before adding raw water.

Raw water from Lac St. Cyr was collected from the raw water influent line to the water treatment plant, while synthetic water was made in the laboratory at the University of Alberta. One litre of raw water sample was placed into the jars and the paddle mixer was lowered into the jars. The appropriate volume of coagulant was added to the addition vials at the front of the DAF unit and water was added to ensure complete transfer of coagulant and to make sure the volume added to the jars was constant. The necessity for accuracy of coagulant concentration and complete coagulant transfer overshadowed the possible consequences of preliminary hydrolysis of the coagulant. The pH was measured but not adjusted. Rapid mix was performed at 400 rpm ($G = 350\ s^{-1}$) for 2 minutes. Flocculation mixing was performed for 10 minutes at a G value determined for the individual experiments. After flocculation, the paddles were removed and the recycle sequence was activated. The jars were allowed to stand for 10 minutes before samples were taken. The samples were obtained from outlets at the base of each jar, which were purged with sample before the samples for analysis were collected. Pictures of the DAF jar tester apparatus are shown in Figures 3.3.2 and 3.3.3.

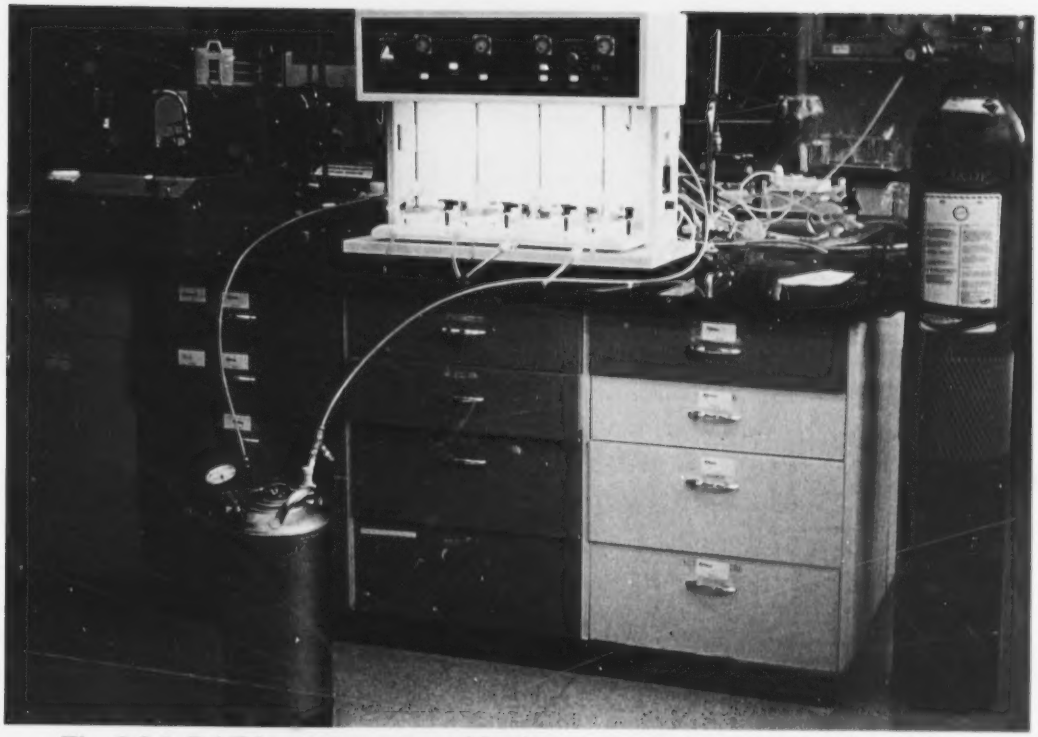


Fig. 3.3.1 DAF jar tester setup with air source, saturator, and DAF unit.

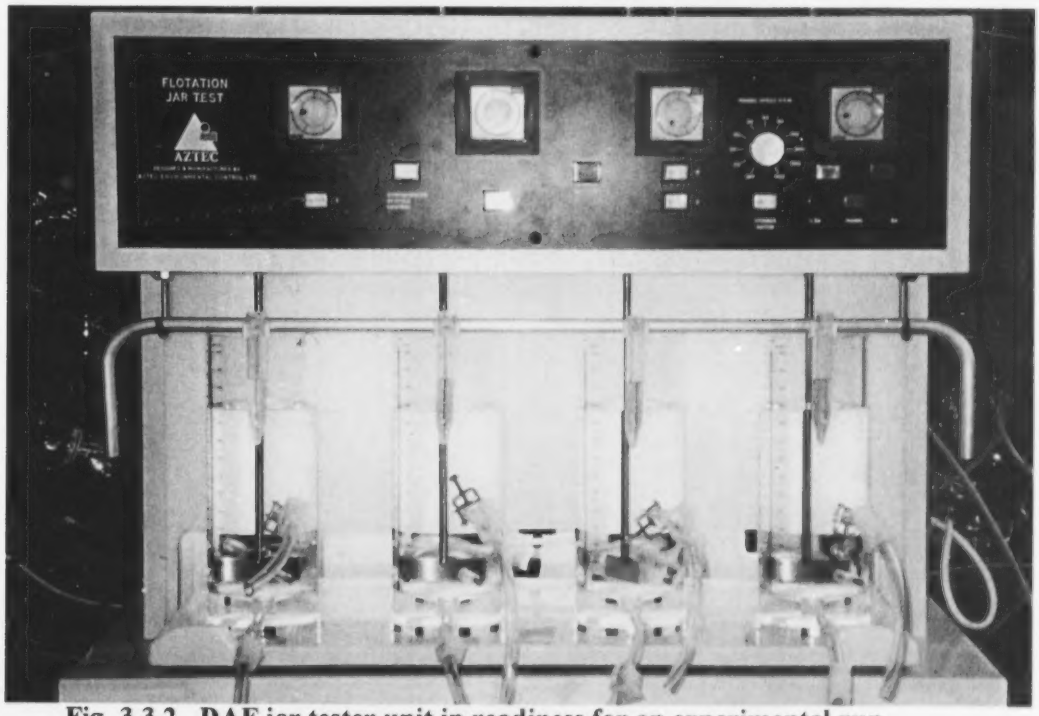


Fig. 3.3.2 DAF jar tester unit in readiness for an experimental run.

3.3.15 Determination of G

Flocculation mixing intensity or G was the parameter investigated to determine the effects of flocculation on DAF performance. The G value depended on the dynamics of the mixing vessel and paddle, the volume of solution, and the speed of the paddles. The G was calculated for various mixing speeds using equation 3.3.1.

$$G = (\{2\pi\omega\tau\}/\{\mu V\})^{1/2} \qquad \text{Eq. 3.3.1}$$

Where: ω is the rotational speed of the paddle in revolutions per second

2π is a conversion factor from revolutions to radians

τ is the net torque applied to the sample

μ is the dynamic viscosity of the water

V is the volume of the sample

A straight line was seen in a plot of G vs. N (revolutions per minute). The equation obtained from this line enabled calculation of corresponding G-values at other mixing speeds. The paddle used was a 20 x 80 x 1.5 mm flat-blade paddle. The cylindrical jars had a diameter of 90 mm and a height of 212 mm to the maximum volume of 1400 mL.

4. RESULTS

4.1 Evaluation of various coagulants and coagulant doses

The performance of the various coagulants was evaluated in terms of percent reduction in four parameters. These parameters were: turbidity, which is a surrogate measure of suspended particulates, true colour and DOC, which are surrogate measures of organic content, and chlorophyll-a, which is a surrogate measure for algae mass. Aluminum residual was measured for aluminum based coagulants, with a lower aluminum residual being desirable. Results of the percent removal of these parameters for each of the eight coagulants are summarized in Figures 4.1.1 to 4.1.4.

The coagulants and coagulant doses with the highest percent removal of DOC and true colour were Ferifloc (4 to 5 mg/L as Fe), alum (125 to 150 mg/L as Al), PASS (50 mg/L as Al), NIAD-1 (30 to 40 mg/L as Al) and Magnifloc 577 (0.1 mg/L). For removal of turbidity, two coagulants gave the highest percent removal. These were NIAD-1 at 20 mg Al/L and PASS at 30 mg Al/L. For the removal of chlorophyll-a, four coagulants gave good performance. These coagulants were Ferifloc (3 mg/L as Fe), alum (75 mg/L as Al), NIAD-1 (50 mg/L as Al) and PASS (15 mg/L as Al). These results are summarized in Table 4.1.1.

Although the effect of changes in pH were not investigated in this study, initial and final pHs were measured and are summarized in Table 4.1.2. An optimum dose for each coagulant was chosen on the basis of best overall performance, taking all parameters into account.

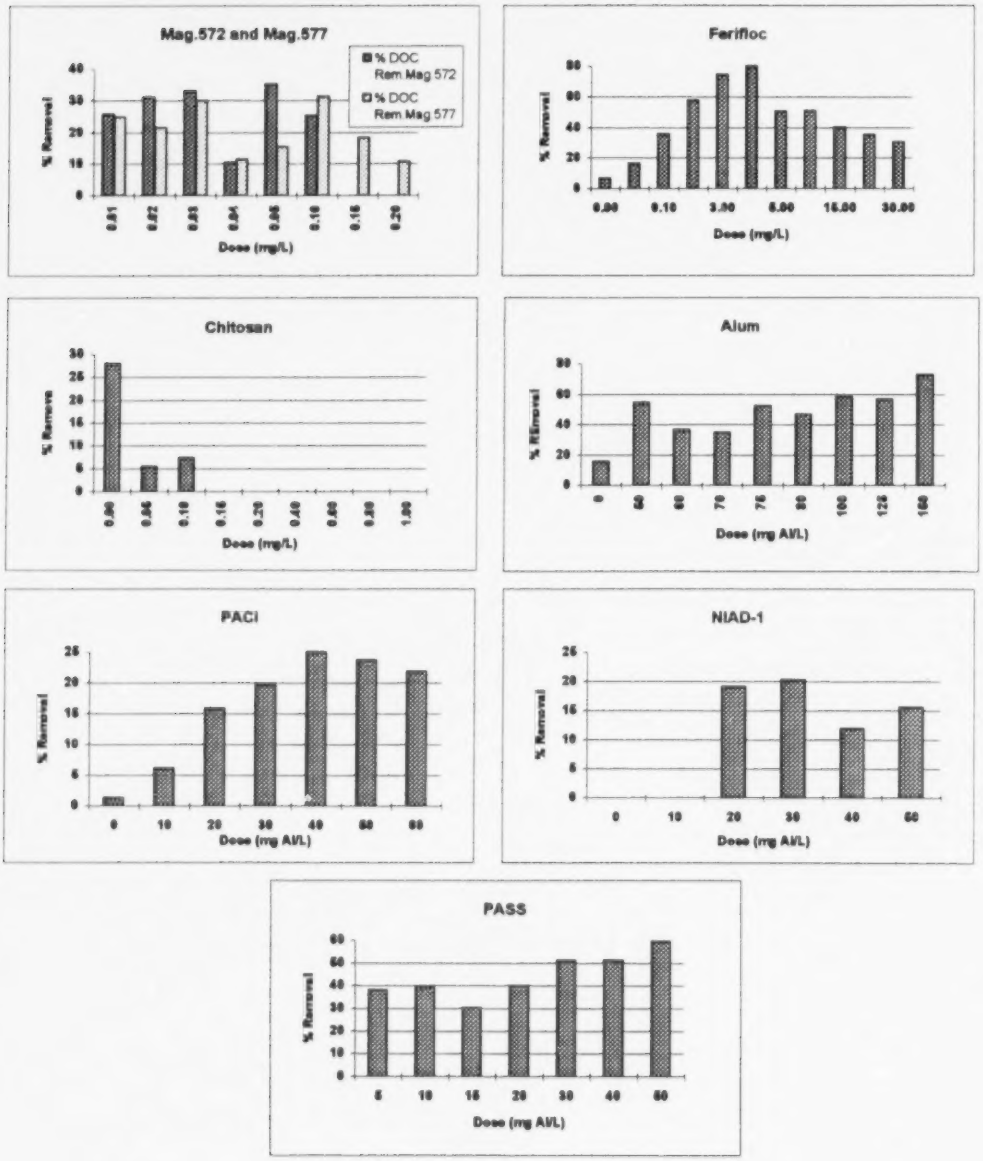


Fig. 4.1.1 Percent removal of DOC for all coagulants

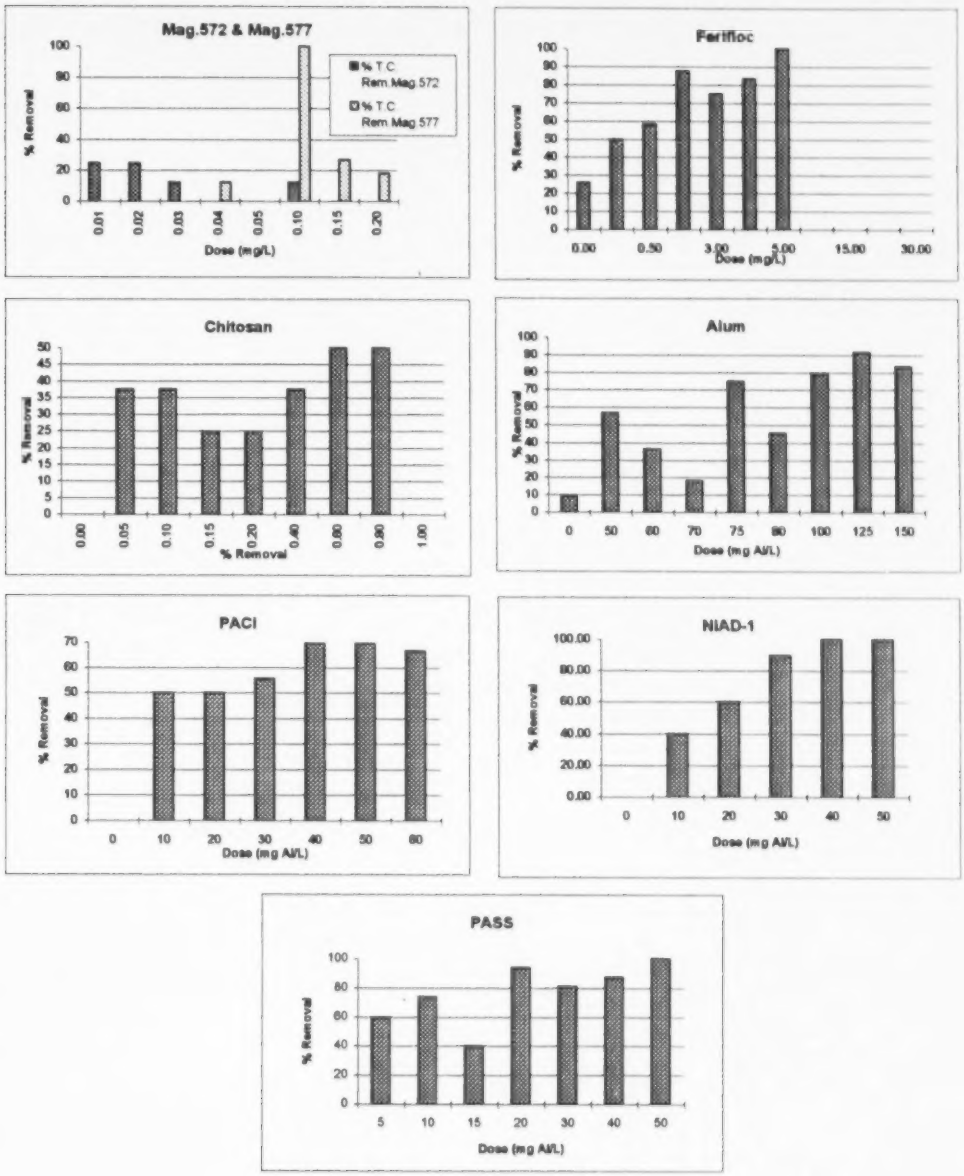


Fig. 4.1.2 Percent removal of true colour for all coagulants

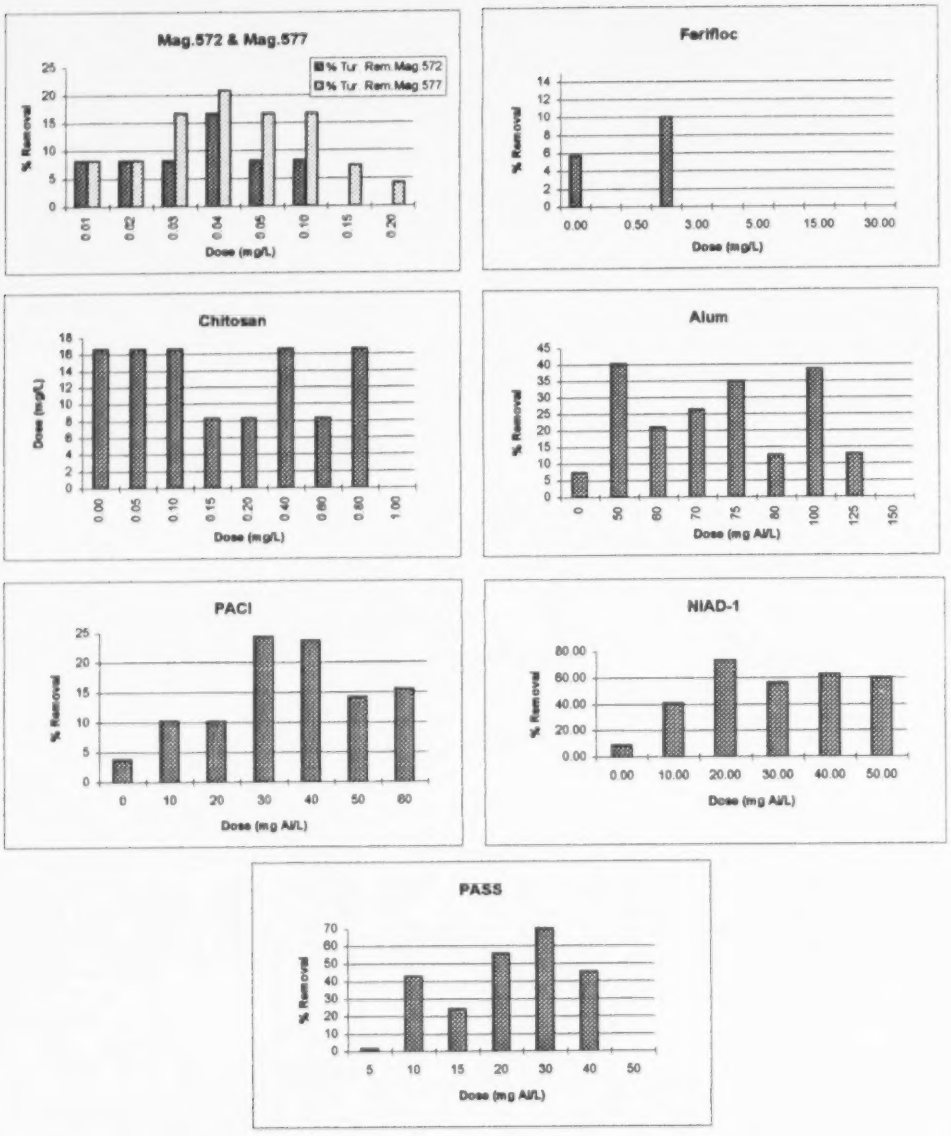


Fig. 4.1.3 Percent removal of turbidity for all coagulants

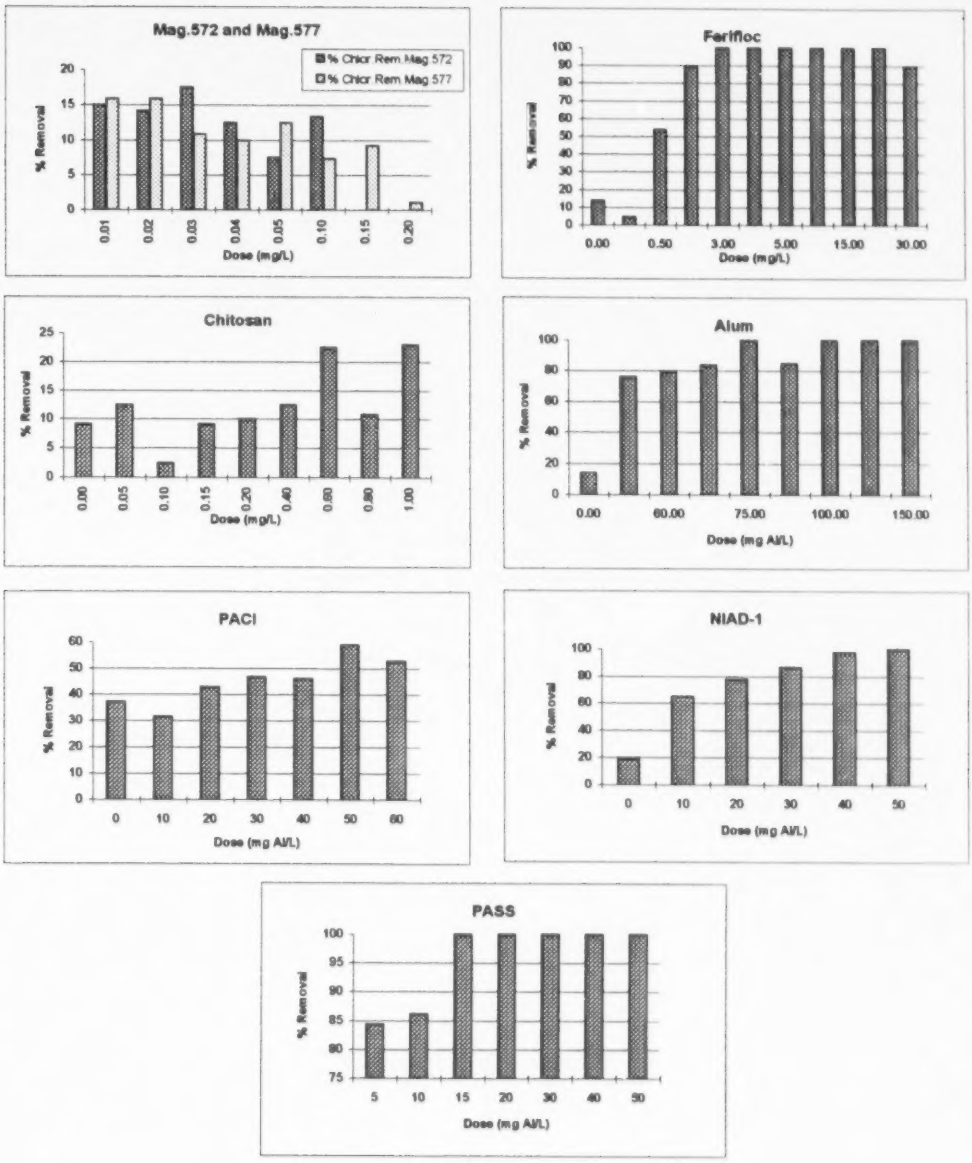


Fig. 4.1.4 Percent removal of chlorophyll-a for all coagulants

Table 4.1.1 Optimum doses and corresponding percent removal for all coagulants

Parameter	Coagulant Type							
	Magnifloc 572	Magnifloc 577	Chitosan	Ferifloc	Alum	PACl	NIAD-1	PASS
Chlorophyll-a								
% Removal	18	16	22	100	100	59	100	100
Optimum Dose (mg/L)	0.03	0.01	0.6	3	75	50	50	15
DOC								
% Removal	35	31	N.O.	80	73	25	20	60
Optimum Dose (mg/L)	0.05	0.1	N.O.	4	150	40	30	50
True Colour								
% Removal	25	100	50	100	90	70	100	100
Optimum Dose (mg/L)	0.01	0.1	0.6	5	125	40	40	50
Turbidity								
% Removal	17	21	N.O.	10	40	24	72	70
Optimum Dose (mg/L)	0.04	0.04	N.O.	2	50	30	20	30

N.O. = No optimum dose

Table 4.1.2 pH of raw and treated water at the optimum dose for each coagulant

Coagulant Type	Optimum Dose (mg/L)	pH Raw	pH Treated
Alum			
Chlorophyll-a	75	8.02	7.03
DOC	150	8.01	6.54
True Color	125	8.02	6.67
Turbidity	50	8.01	7.32
PASS			
Chlorophyll-a	15	8.04	7.32
DOC	50	8.15	6.54
True Color	50	8.15	6.54
Turbidity	30	8.04	6.97
PACl			
Chlorophyll-a	50	7.99	7.64
DOC	40	7.99	7.75
True Color	40	7.99	7.75
Turbidity	30	7.99	7.82
NIAD-1			
Chlorophyll-a	50	8.15	7.31
DOC	30	8.15	7.64
True Color	40	8.15	7.42
Turbidity	20	8.15	7.75
Ferifloc			
Chlorophyll-a	3	8.02	6.47
DOC	4	8.02	5.71
True Color	5	8.04	4.86
Turbidity	2	8.02	6.78
Magnifloc 572			
Chlorophyll-a	0.03	8.05	8.13
DOC	0.05	8.05	8.15
True Color	0.01	8.05	8.07
Turbidity	0.04	8.05	8.13
Magnifloc 577			
Chlorophyll-a	0.01	8.05	8.13
DOC	0.1	8.05	8.16
True Color	0.1	8.05	8.16
Turbidity	0.04	8.05	8.15
Chitosan			
Chlorophyll-a	0.6	8.05	7.33
DOC	-		
True Color	0.6	8.05	7.33
Turbidity	-		

In choosing the best coagulants, DAF performance and aluminum residual were considered, as well as dosage. A summary of the aluminum residuals of three of the aluminum-based coagulants are given in Table 4.1.3.

Table 4.1.3 Aluminum residuals of filtered samples after DAF treatment

Coagulant	Dose (mg/L)	Al residual (mg/L)
Alum	100	0.70
PASS	30	0.45
NIAD-1	30	0.28

Dosage was used to determine the more desirable coagulant if two coagulants were equal in all other respects, with a lower dose being more desirable. Five of the eight coagulants were analyzed in the statistical tests.

From the analytical results, it can be concluded that NIAD-1 and PASS have good performance for the four parameters. Both coagulants were found to have low aluminum residuals, and treated pH values close to neutral. These coagulants were chosen as the aluminum based coagulants in the statistical tests at their optimum dose of 30 mg/L. Ferifloc showed excellent removal of organics and algae at a dose of 2 mg/L, but poor performance with turbidity. At greater or lesser dosages than the optimum, Ferifloc actually increased the turbidity of the water above the turbidity of the source water. Instead of recording a negative value, this result was recorded as 0% reduction. However, on the strength of its

performance with the other parameters, Ferifloc was used in the statistical tests to compare the performance of an iron-based coagulant with an aluminum-based coagulant. The organic polymers Magnifloc 577 and 572 showed poor performance as a primary coagulant for all four parameters, as did Chitosan. However, in the interests of comparing different types of coagulants, Magnifloc 577 and 572 were used in the statistical tests to compare organic polymers and metal-based coagulants.

4.2 Statistical evaluation of certain coagulants at optimum doses

Experiments and two replicates were run with the five chosen coagulants at their optimum doses. The results are summarized in Table 4.2.1 as percent reduction in the DAF performance parameters. Student t-tests were performed at the 95% and 99% confidence limits at the optimum doses of the coagulants. All coagulants were compared with the control jar to which no coagulant was added to determine whether the effects were the result of coagulant addition, or merely DAF. The results of the t-tests are shown in Tables 4.2.2 to 4.2.5. These results showed that PASS, NIAD-1 and Ferifloc gave a significant difference from the control jar for chlorophyll-a reduction while Magnifloc 572 and 577 showed no significant difference from the control jar. The same results were obtained for DOC removal with the exception that Magnifloc 577 and 572 showed a significant effect. Turbidity reduction results were similar to chlorophyll-a reduction. All coagulants showed significant effects for true colour reduction except for

Magnifloc 577. The coagulants were ranked according to DAF performance for each case measured. These rankings are summarized in Table 4.2.6, where the coagulant with the best performance is listed first.

From this table, it can be said that NIAD-1 gives the best performance with respect to true colour and turbidity, and is second best for chlorophyll-a and DOC. As seen in Table 4.1.4, NIAD-1 also has the lowest aluminum residual. Therefore, NIAD-1 was chosen as the aluminum-based coagulant to be used in the pilot-scale study. Ferifloc performed best with respect to DOC and true colour, second best for chlorophyll-a removal, and third best in terms of turbidity. However, it was decided to use Ferifloc in the pilot scale study to compare an aluminum-based and iron-based coagulant. Magnifloc 572 and 577 performed so poorly that they were not included in further experiments. ANOVA analysis confirmed the t-test results.

Table 4.2.1 Summary of percent reduction for DAF performance parameters

	Coagulant Type				
	PASS	NIAD-1	Ferifloc	Mag 572	Mag 577
Coag. con. (mg/L)	30	30	2	0.01	0.1
	% reduction				
Chlorophyll-a					
Exp#1	100.0	87.5	93.8	14.8	1.9
Exp#2	100.0	89.8	90.6	7.7	2.6
Exp#3	100.0	89.8	89.1	9.0	1.3
average (X)	100.0	89.1	91.1	10.5	1.9
std. dev.(S)	0.0	1.4	2.4	3.8	0.6
DOC					
Exp#1	34.9	34.0	67.8	0.0	7.3
Exp#2	39.7	36.4	65.3	0.0	5.9
Exp#3	33.0	37.3	64.7	0.4	4.0
average (X)	35.9	35.9	66.0	0.1	5.7
std. dev.(S)	3.4	1.7	1.6	0.2	1.6
True Color					
Exp#1	81.3	100.0	100.0	50.0	50.0
Exp#2	87.5	93.8	93.8	50.0	60.0
Exp#3	81.3	100.0	100.0	50.0	30.0
average (X)	83.3	97.9	97.9	50.0	46.7
std. dev.(S)	3.6	3.6	3.6	0.0	15.3
Turbidity					
Exp#1	56.3	71.9	41.9	0.0	0.0
Exp#2	62.5	78.1	37.5	6.7	13.3
Exp#3	62.5	68.8	31.3	6.7	6.7
average (X)	60.4	72.9	36.9	4.4	6.7
std. dev.(S)	3.6	4.8	5.3	3.8	6.7

Table 4.2.2 Summary of t-tests for Chlorophyll-a removal

Control vs all coagulants

	At α = 0.05				At α = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
PASS	2.13	71.62	y	sig. difference	3.75	71.62	y	sig. difference
NIAD-1	2.13	55.40	y	sig. difference	3.75	55.40	y	sig. difference
Ferifloc	2.13	46.10	y	sig. difference	3.75	46.10	y	sig. difference
Mag 572	2.13	0.41	n	no difference	3.75	0.41	n	no difference
Mag 577	2.13	-2.89	n	no difference	3.75	-2.89	n	no difference

PASS vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
NIAD-1	2.13	14.00	y	sig. difference	3.75	14.00	y	sig. difference
Ferifloc	2.13	6.43	y	sig. difference	3.75	6.43	y	sig. difference
Mag 572	2.13	40.99	y	sig. difference	3.75	40.99	y	sig. difference
Mag 577	2.13	263.27	y	sig. difference	3.75	263.27	y	sig. difference

NIAD-1 vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Ferifloc	2.13	-1.32	n	no difference	3.75	-1.32	n	no difference
Mag 572	2.13	33.87	y	sig. difference	3.75	33.87	y	sig. difference
Mag 577	2.13	100.67	y	sig. difference	3.75	100.67	y	sig. difference

Ferifloc vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 572	2.13	31.23	y	sig. difference	3.75	31.23	y	sig. difference
Mag 577	2.13	62.50	y	sig. difference	3.75	62.50	y	sig. difference

Magnifloc 572C vs Magnifloc 577C

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 577	2.13	3.89	y	sig. difference	3.75	3.89	y	sig. difference

Table 4.2.3 Summary of t-tests for DOC removal

Control vs all coagulants

	At α = 0.05				At α = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
PASS	2.13	-8.05	y	sig. difference	3.75	-8.05	y	sig. difference
NIAD-1	2.13	-8.98	y	sig. difference	3.75	-8.98	y	sig. difference
Ferifloc	2.13	-17.65	y	sig. difference	3.75	-17.65	y	sig. difference
Mag 572	2.13	2.47	y	sig. difference	3.75	2.47	n	no difference
Mag 577	2.13	-2.38	y	sig. difference	3.75	-2.38	n	no difference

PASS vs. other Coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
NIAD-1	2.13	0.00	n	no difference	3.75	0.00	n	no difference
Ferifloc	2.13	-13.66	y	sig. difference	3.75	-13.66	y	sig. difference
Mag 572	2.13	17.96	y	sig. difference	3.75	17.96	y	sig. difference
Mag 577	2.13	13.71	y	sig. difference	3.75	13.71	y	sig. difference

NIAD-1 vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Ferifloc	2.13	-21.96	y	sig. difference	3.75	-21.96	y	sig. difference
Mag 572	2.13	35.90	y	sig. difference	3.75	35.90	y	sig. difference
Mag 577	2.13	22.08	y	sig. difference	3.75	22.08	y	sig. difference

Ferifloc vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 572	2.13	68.70	y	sig. difference	3.75	68.70	y	sig. difference
Mag 577	2.13	44.97	y	sig. difference	3.75	44.97	y	sig. difference

Magnifloc 572C vs Magnifloc 577C

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 577	2.13	-5.84	y	sig. difference	3.75	-5.84	y	sig. difference

Table 4.2.4 Summary of t-tests for true color removal

Control vs all coagulants

	At α = 0.05				At α = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
PASS	2.13	-12.97	y	sig. difference	3.75	-12.97	y	sig. difference
NIAD-1	2.13	-16.10	y	sig. difference	3.75	-16.10	y	sig. difference
Ferifloc	2.13	-16.10	y	sig. difference	3.75	-16.10	y	sig. difference
Mag 572	2.13	-12.07	y	sig. difference	3.75	-12.07	y	sig. difference
Mag 577	2.13	-3.48	y	sig. difference	3.75	-3.48	n	no difference

PASS vs. other Coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
NIAD-1	2.13	-4.95	y	sig. difference	3.75	-4.95	y	sig. difference
Ferifloc	2.13	-4.95	y	sig. difference	3.75	-4.95	y	sig. difference
Mag 572	2.13	16.00	y	sig. difference	3.75	16.00	y	sig. difference
Mag 577	2.13	4.05	y	sig. difference	3.75	4.05	y	sig. difference

NIAD-1 vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Ferifloc	2.13	0.00	n	no difference	3.75	0.00	n	no difference
Mag 572	2.13	23.00	y	sig. difference	3.75	23.00	y	sig. difference
Mag 577	2.13	5.66	y	sig. difference	3.75	5.66	y	sig. difference

Ferifloc vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 572	2.13	23.00	y	sig. difference	3.75	23.00	y	sig. difference
Mag 577	2.13	5.66	y	sig. difference	3.75	5.66	y	sig. difference

Magnifloc 572C vs Magnifloc 577C

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 577	2.13	0.38	n	no difference	3.75	0.38	n	no difference

Table 4.2.5 Summary of t-tests for turbidity removal

Control vs all coagulants

	At α = 0.05				At α = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
PASS	2.13	-29.00	y	sig. difference	3.75	-29.00	y	sig. difference
NIAD-1	2.13	-26.46	y	sig. difference	3.75	-26.46	y	sig. difference
Ferifloc	2.13	-11.96	y	sig. difference	3.75	-11.96	y	sig. difference
Mag 572	2.13	-1.55	n	no difference	3.75	-1.55	n	no difference
Mag 577	2.13	-1.34	n	no difference	3.75	-1.34	n	no difference

PASS vs. other Coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
NIAD-1	2.13	-3.62	y	sig. difference	3.75	-3.62	n	no difference
Ferifloc	2.13	6.33	y	sig. difference	3.75	6.33	y	sig. difference
Mag 572	2.13	18.38	y	sig. difference	3.75	18.38	y	sig. difference
Mag 577	2.13	12.28	y	sig. difference	3.75	12.28	y	sig. difference

NIAD-1 vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Ferifloc	2.13	8.72	y	sig. difference	3.75	8.72	y	sig. difference
Mag 572	2.13	19.34	y	sig. difference	3.75	19.34	y	sig. difference
Mag 577	2.13	13.99	y	sig. difference	3.75	13.99	y	sig. difference

Ferifloc vs other coagulants

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 572	2.13	8.53	y	sig. difference	3.75	8.53	y	sig. difference
Mag 577	2.13	6.13	y	sig. difference	3.75	6.13	y	sig. difference

Magnifloc 572C vs Magnifloc 577C

	At a = 0.05				At a = 0.01			
	t_{crit}	t_{calc}	Reject Ho ?	Interpretation	t_{crit}	t_{calc}	Reject Ho ?	Interpretation
Mag 577	2.13	-0.50	n	no difference	3.75	-0.50	n	no difference

Table 4.2.6 Ranking of Coagulants at Optimum Doses

Parameter	Ranking of Coagulants
Chlorophyll-a	PASS NIAD-1 & Ferifloc Magnifloc 577 Magnifloc 572
DOC	Ferifloc NIAD-1 & PASS Magnifloc 577 Magnifloc 572
True Colour	NIAD-1 & Ferifloc PASS Magnifloc 577 & 572
Turbidity	NIAD-1 PASS Ferifloc Magnifloc 577 & 572

4.3 Pilot plant evaluation of flocculation mixing intensity and time

NIAD-1 and Ferifloc were used as coagulants for this experiment. Originally a 2^3 factorial design was carried out using coagulant type, flocculation mixing intensity and time as the three variables. However, Ferifloc was found to decrease the water quality to such an extent that it was excluded from the analysis and subsequent experiments. It is thought that calibration of the coagulant feed pump was not correct and therefore overdosing of both the coagulants occurred. This did not affect the performance of NIAD-1 as the optimum dose range was quite wide. However, Ferifloc had a very narrow optimum dose range, therefore minor overdosing would have a large adverse effect on treated water quality. The results of a 2^2 factorial design are presented here.

DAF performance in the pilot plant was measured by percent reduction of turbidity, true colour, chlorophyll-a, and DOC. The results are shown in Table 4.3.1. The factorial analysis is shown in Table 4.3.2 with a diagrammatic summary in Fig. 4.3.1.

In Table 4.3.2, the main and interaction effects are calculated by a series of computations specific to factorial design. The row entitled "sum" is calculated by multiplying the numbers in the columns entitled 1, G, T, and GT by the numbers in the "reduction" column and then adding the results. for example, the sum in column G is obtained by adding -40, 39, -48, and 47 together. The divisor is the number of elements that affect the results. In the case of column G, the divisor is

4. The effect is the numerical result of twice the sum divided by the divisor. For column G, the effect is (-2/4)*2, which equals -1. The effects can be seen more easily by the summary diagram in Fig. 4.3.1.

Table 4.3.1 Experimental results for pilot scale study using NIAD-1

			Percent reduction			
Exp. no.	**G (s^{-1})**	**T (min.)**	**Turbidity**	**True colour**	**Chlorophyll-a**	**DOC**
1	30	12	40	25	87	42
2	70	12	39	92	79	17
3	30	24	48	92	86	32
4	70	24	47	33	91	32

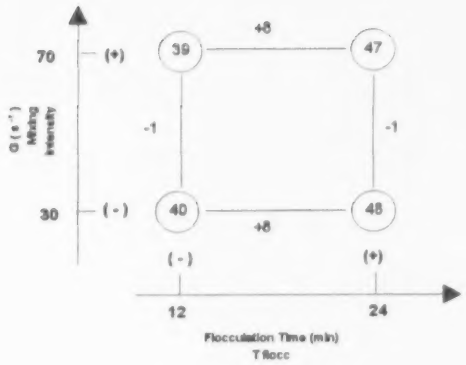
Table 4.3.2 Analysis of Factorial Design

Turbidity					
	1	G	T	GT	reduction
1	1	-1	-1	1	40
G	1	1	-1	-1	39
T	1	-1	1	-1	48
GT	1	1	1	1	47
sum	174	-2	16	0	
divisor	8	4	4	4	
effect	43.5	-1	8	0	

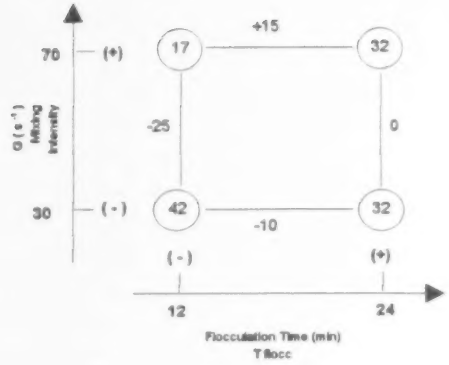
True colour					
	1	G	T	GT	reduction
1	1	-1	-1	1	25
G	1	1	-1	-1	92
T	1	-1	1	-1	92
GT	1	1	1	1	33
sum	242	8	8	-126	
divisor	8	4	4	4	
effect	60.5	4	4	-63	

DOC					
	1	G	T	GT	reduction
1	1	-1	-1	1	42
G	1	1	-1	-1	17
T	1	-1	1	-1	32
GT	1	1	1	1	32
sum	123	-25	5	25	
divisor	8	4	4	4	
effect	30.75	-12.5	2.5	12.5	

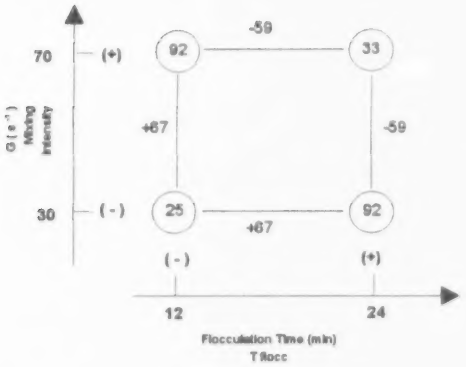
Chlorophyll-a					
	1	G	T	GT	reduction
1	1	-1	-1	1	87
G	1	1	-1	-1	79
T	1	-1	1	-1	86
GT	1	1	1	1	91
sum	343	-3	11	13	
divisor	8	4	4	4	
effect	85.75	-1.5	5.5	6.5	



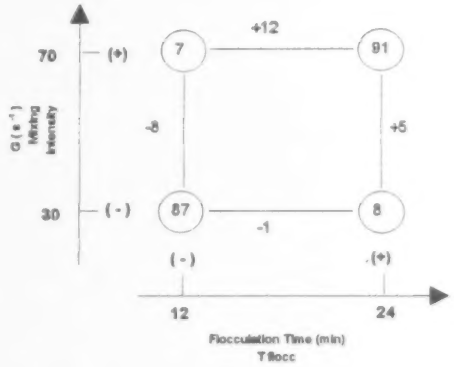
G - T_{floc} interaction for turbidity



G - T_{floc} interaction for DOC



G - T_{floc} interaction for true color



G - T_{floc} interaction for chlorophyll-a

Fig. 4.3.1 GT interaction diagram for all DAF performance parameters

The main effect on mixing intensity (G) was the measure of the average effect of the mixing intensity over all conditions of the flocculation time (T). The same applies to the flocculation time. Flocculation time and mixing intensity are said to interact as they did not behave additively. The main and interaction effects are summarized in Table 4.3.3.

Table 4.3.3 Summary of main and interaction effects

	Turbidity	**DOC**	**True colour**	**Chlorophyll-a**
G main effect (as G increases from 30 s^{-1} to 70 s^{-1})	1% reduction	12.5 % reduction	4 % increase	1.5 % reduction
T main effect (as T increases from 12 to 24 min.)	8% increase	2.5 % increase	4 % increase	5.5 % increase
GT interaction (as both G and T increase from low to high values)	No effect	12.5 % increase	63 % reduction	6.5 % increase

The most beneficial main effect was that of mixing intensity. There was a reduction in turbidity, DOC and chlorophyll-a when the mixing intensity was increased from 30 s^{-1} to 70 s^{-1}. The decrease in these parameters is not large, with the exception of DOC. The increase in true colour is very slight. An improvement in DAF efficiency from a lower to a higher mixing intensity is expected as much literature states that smaller or "pinpoint" flocs are optimal for DAF performance (Edzwald and Malley, 1990; Janssens, 1991; Malley and Edzwald, 1991; Edzwald et al., 1992; Bunker et al., 1994; Odegaard, 1994). However, as will be seen in the following experiments, it is possible that there was not enough spread in the mixing intensity values to show much effect.

An increase in flocculation time shows a decrease in DAF performance, but again, not with much effect. Subsequent experiments show that a very short flocculation time is required, and perhaps even the low value in this experiment was too high to show any effect.

An interesting interaction effect is seen between the variables. With an increase in both the variables, a decrease in true colour of 63% was seen. In the other performance parameters, either a decrease in water quality or no effect was observed. This is a difficult phenomenon to explain and would merit further investigation. Due to the lack of convincing results and the loss of a variable, it was decided not to pursue this course of study further. Bench scale analysis of the

effect of flocculation mixing intensity were undertaken in an effort to understand the effect of this variable on DAF performance.

4.4 Evaluation of variation of flocculation mixing intensity using synthetic water

It was necessary to determine the optimum dose of coagulant for these experiments as the spiked synthetic water had different qualities than the natural water, especially in terms of organics and suspended particles. Every effort was made to provide the same hardness and alkalinity as the natural water. PACl was chosen as the coagulant for the remaining experiments due to its performance in the screening tests and its known properties. The optimum dose of PACl was determined to be 1 mg/L as is shown in Fig. 4.4.1 and by the EPM data in Fig. 4.4.2.

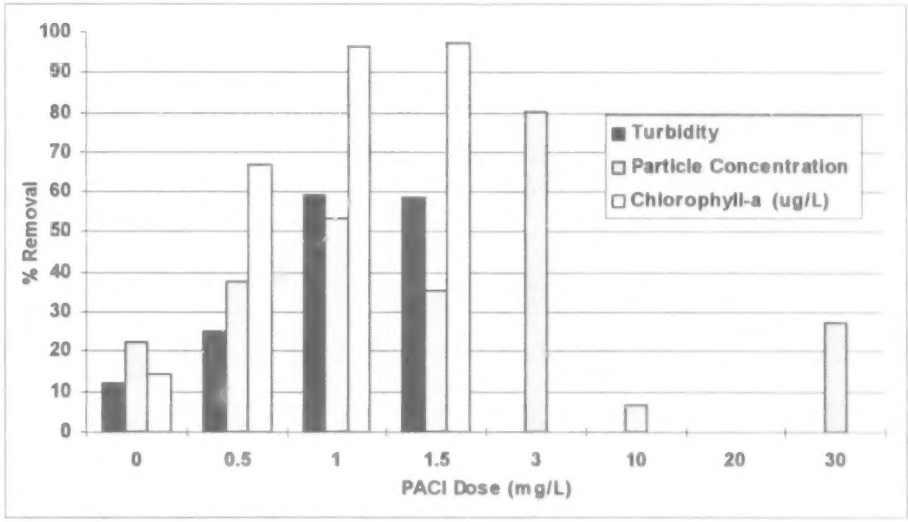


Fig. 4.4.1 Determination of optimum PACl dose for synthetic water using DAF performance parameters

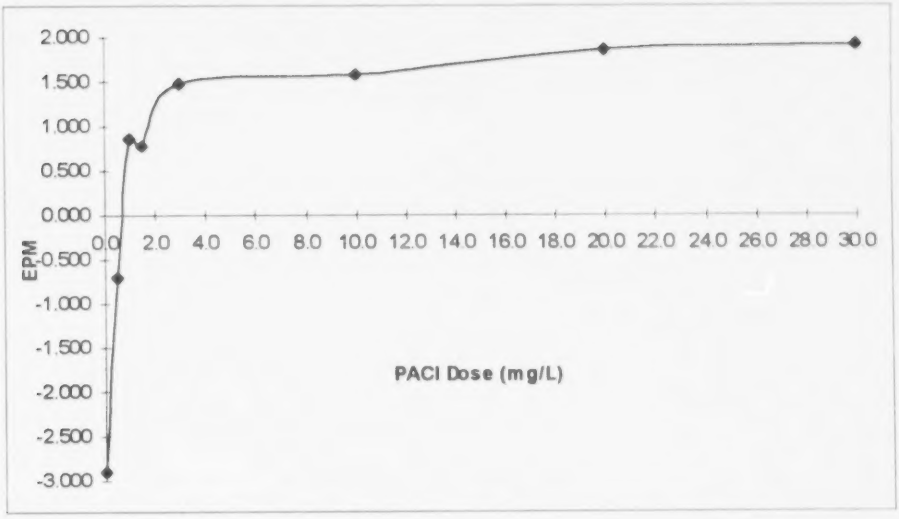


Fig. 4.4.2 Determination of optimum dose of PACl for synthetic water using EPM measurements

The next part of the experiment involved varying the flocculation mixing intensity and observing DAF performance in terms of percent reduction of turbidity, particle count, and chlorophyll-a. True colour was not used as a parameter since no dissolved organic material was added and any organics added by the algae were below the detection limit of the Milton Roy Spectronic 601. A summary of the percent removal of the various parameters with respect to the mixing intensity is shown in Fig. 4.4.3. The reduction of chlorophyll-a, turbidity, and particle count increased with increasing mixing intensity up to a certain value, after which no improvement was observed. The best performance was achieved at 100 rpm ($G = 250\ s^{-1}$) with almost 100% reduction in chlorophyll-a concentration and particle count, and 80% reduction in turbidity. This mixing speed gives a

mixing intensity that is very close to the mixing intensity reported in the literature as the optimum value for DAF.

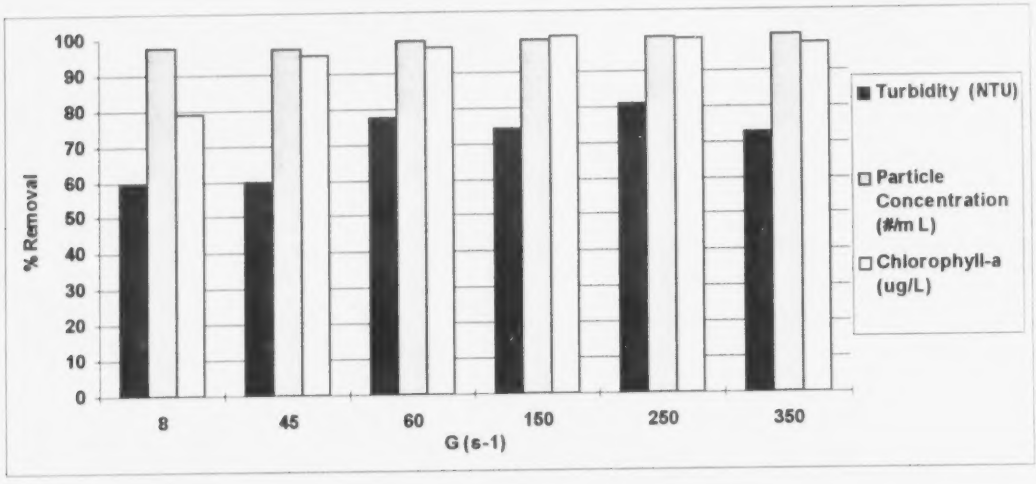


Fig. 4.4.3 Effect of mixing intensity on measured parameters for synthetic water

4.5 Evaluation of variation of flocculation mixing intensity using Lac St. Cyr water

The optimum dose of coagulant was determined as the quality of the raw water changed slightly from the initial screening experiments, which were carried out in the summer. The water for this stage was collected in the Fall. The optimum dose of PACl was determined to be 25 mg/L as determined by the percent reduction of turbidity, particle count, DOC, UV absorption at 254 nm, and chlorophyll-a. These are summarized in Fig. 4.5.1. EPM data were also used. The EPM value at the optimum dose was -0.56 μm/sec/volt/cm compared to an EPM value of -1.32 μm/sec/volt/cm for the spiked raw water. The optimum dose is considerably higher than the dose for synthetic water, most likely due to the higher organic content of the natural water.

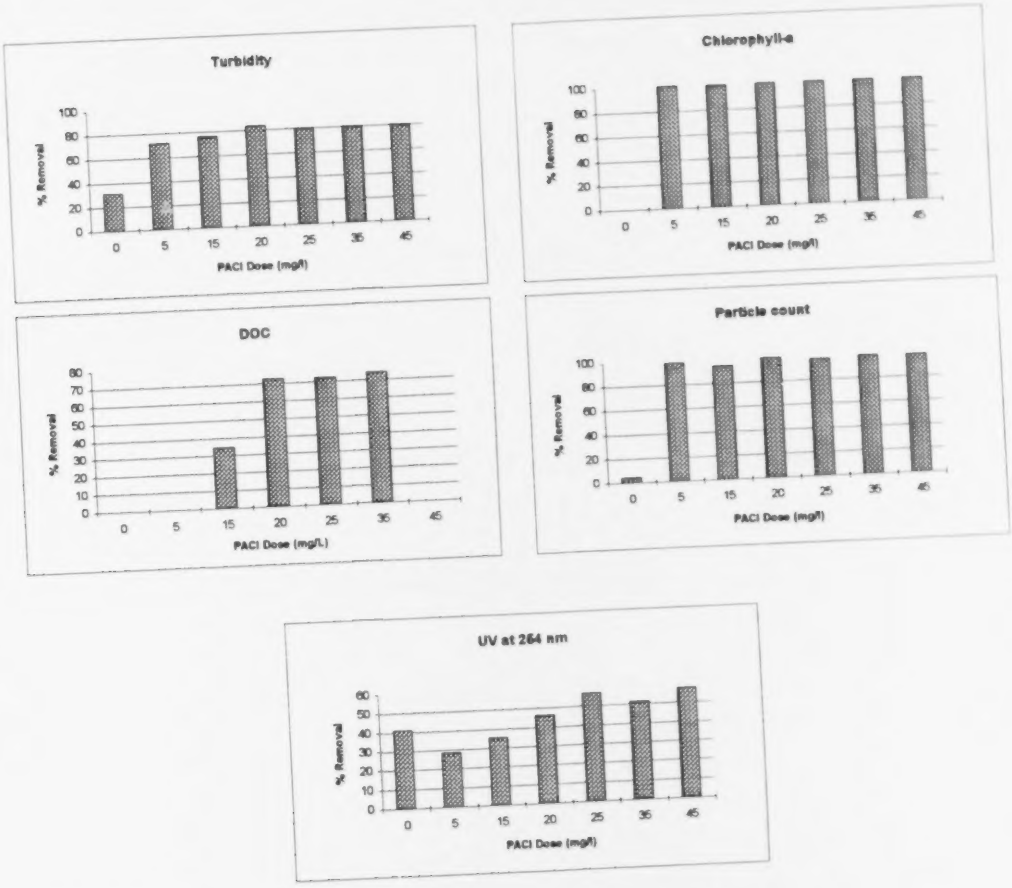


Fig. 4.6.1 Determination of optimum PACl dose on natural water using DAF performance parameters

As for the synthetic water, the next part of the experiments involved varying the flocculation mixing intensity and determining the performance of DAF. A summary of the results are shown in Fig. 4.5.2.

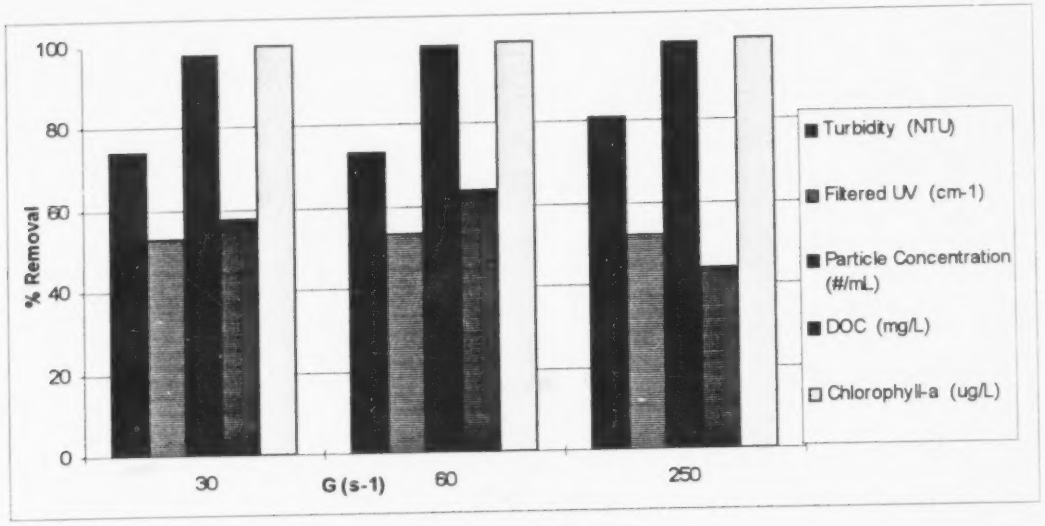


Fig. 4.5.2 Effect of mixing intensities on measured parameters for natural water

The treated water quality improved as the mixing intensity increased from 30 s^{-1} to 60 s^{-1}, although most parameters remained unaffected. The percent reduction of DOC increased as the mixing intensity increased to 60 s^{-1} and decreased as the mixing intensity increased to 250 s^{-1}. However, percent removal of turbidity increased as mixing intensity increased from 60 s^{-1} to 250 s^{-1}. These values of mixing intensity were chosen as they represent the high and low values commonly used in full-scale water treatment plants.

4.6 Investigation of the relationship between flocculation mixing intensity, particle size distribution, and DAF performance.

In this stage of the experiments, it was important to define what was under investigation. It was necessary to break down the results to look at the relationship between flocculation mixing intensity, particle size distribution and DAF performance individually, and in various combinations. First, a basic comparison of DAF performance with respect to the various flocculation mixing intensities was done using reduction of turbidity, chlorophyll-a and particle count as parameters. However, it must be stressed that while this analysis seems to be comparing various flocculation mixing intensities, it is really comparing the particle size distribution created by the mixing intensities after 10 minutes of flocculation. The problem then becomes one of evaluating the relationship of particle size distribution with DAF performance and the relationship of flocculation mixing intensity with particle size distribution. This was done both graphically and numerically as outlined below.

Initially, it was necessary to determine that there was indeed a difference in DAF performance at various flocculation mixing intensities and particle size distributions. This was done by doing ANOVA tests on the turbidity, chlorophyll-a, and particle count data obtained from the samples after DAF. From this analysis it was found that at 10 minutes, flocculation at 100 rpm results in the most effective DAF performance as measured by percent reduction of turbidity, chlorophyll-a, and particle count. Plots of the data (Fig. 4.6.1) do not give definitive results, which is why the statistical tests are necessary. The ANOVA

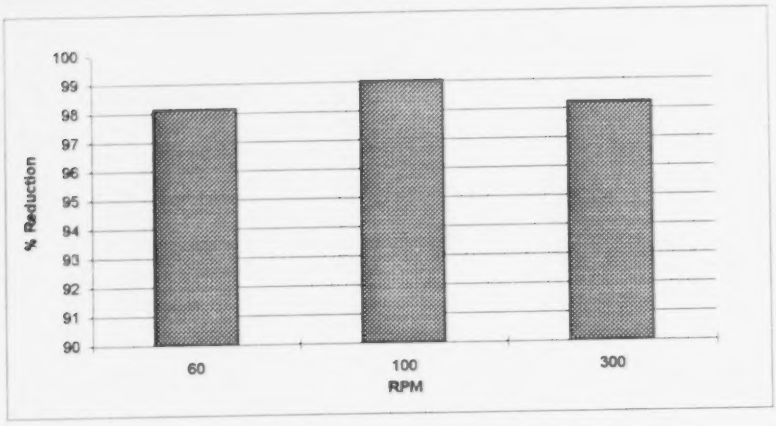


Fig. 4.6.1a Percent reduction in total number of particles

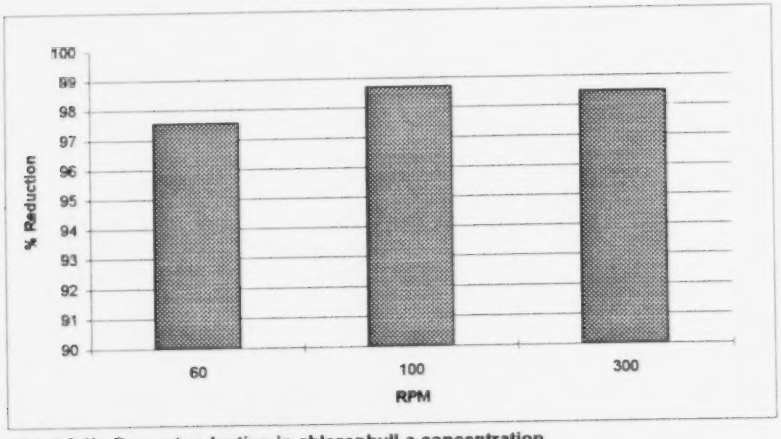


Fig. 4.6.1b Percent reduction in chlorophyll-a concentration

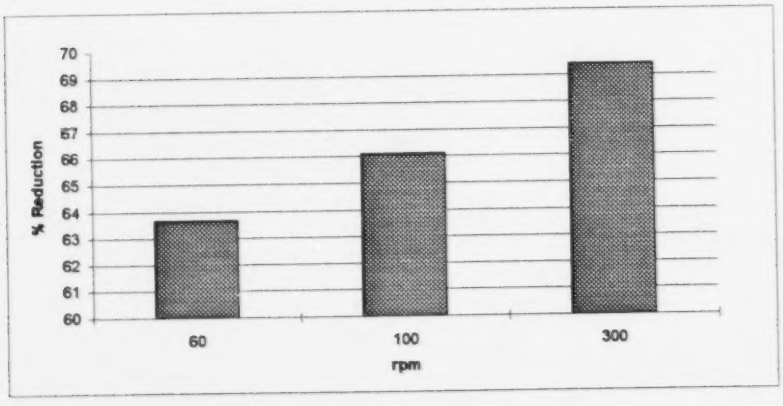


Fig. 4.6.1c Percent reduction in turbidity

Fig.4.6.1a,b,c. DAF performance data

results reveal that there are significant differences between the flocculation mixing intensities for chlorophyll-a and particle count at the 95% level, but not for turbidity. Post-hoc ANOVA tests on the particle count data reveal that there is a difference between counts at 100 rpm, and 60 and 300 rpm, but counts at 60 and 300 rpm are not statistically different from each other. The results of the same tests for chlorophyll-a reveal that there is a difference between 60 rpm and 100 rpm, but none between 100 and 300 rpm. This would suggest that 100 rpm still provides the optimum particle size distribution after 10 minutes of flocculation, since it is cost-effective in a full-scale plant to choose the lowest possible flocculation mixing intensity. These tests gave an idea of the optimum particle size distribution for DAF performance. However, in order to evaluate the relationship between particle size distribution and DAF performance more effectively, other graphical methods were used.

By plotting the volume concentration distribution and number concentration distribution at 10 minutes (end of flocculation) and 20 minutes (after DAF) for all flocculation mixing intensities, it was possible to get a clearer view of the relationship between particle size distribution and DAF performance. Volume concentration per unit volume distributions were plotted as $N\pi d_p^3/6$ vs. d_p where N is the number of particles per mL counted for each size range, and d_p is the mean diameter of the particles for each size range. In calculating the volume of the particles, it was assumed that the particles were spherical. Number concentration distributions were plotted as N vs. d_p. The percent reduction of particles in each size range was calculated and plotted. These graphs help determine the size range in which particles are most effectively removed by DAF.

The volume concentration distributions for 60 rpm (Fig. 4.6.2 and 4.6.3) show reduction in concentration of all sizes of particles. The highest removal of particles occurred in the size range of 9 to 12.5 μm where the removal of particles was virtually 100%. Above and below these sizes, there was less reduction, although there was more reduction at higher size ranges than at lower size ranges. At 100 rpm (Fig. 4.6.4 and 4.6.5), optimum removal of particles occurred between 7 and 12.5 μm, although there was reduction at all size ranges. The percent reduction of particle volume at 300 rpm (Fig. 4.6.6 and 4.6.7) differed from the previous trends. There was reduction at all size ranges except at 22.5 μm, the largest size measured. At this size range there was an increase in the volume

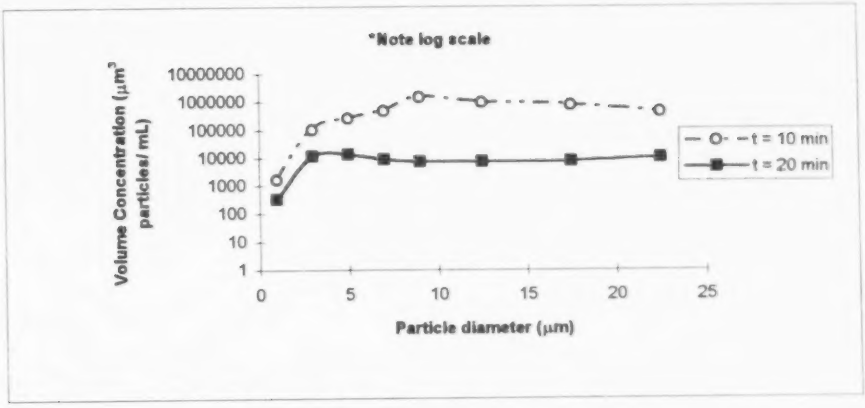


Fig. 4.6.2. Volume concentration of particles from after flocculation (10 min) and after DAF (20 min) for 60 rpm

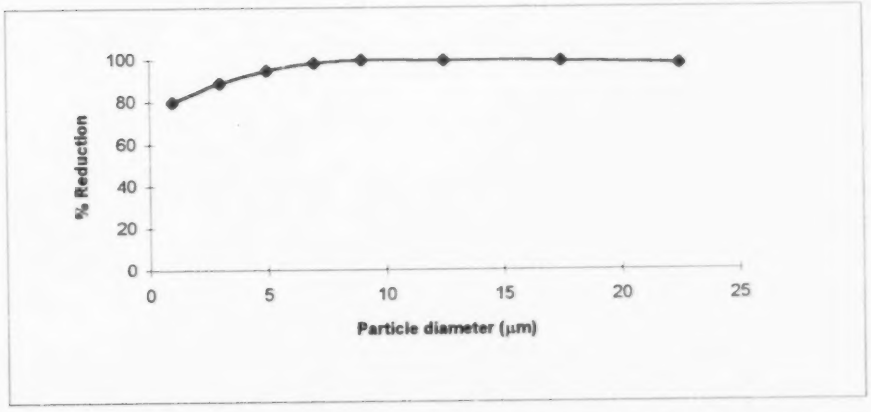


Fig. 4.6.3. Percent reduction of volume concentration after flocculation (10 min) and after DAF (20 min) at 60 rpm

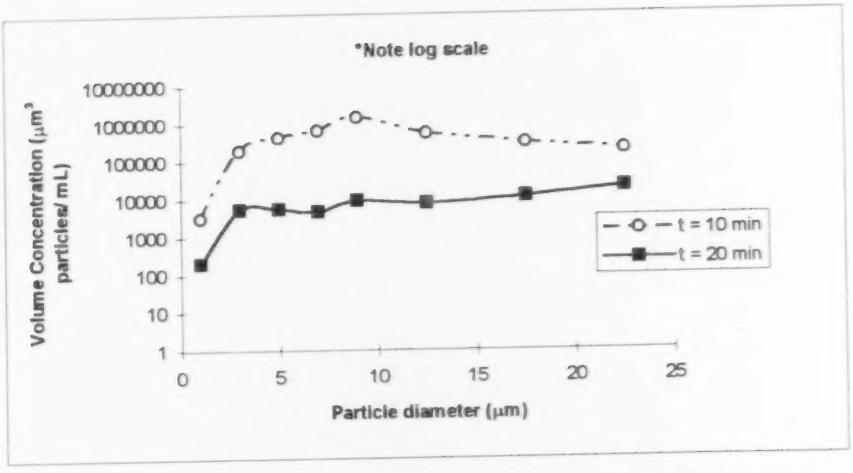


Fig. 4.6.4. Volume concentration of particles after flocculation (10 min) and after DAF (20 min) at 100 rpm

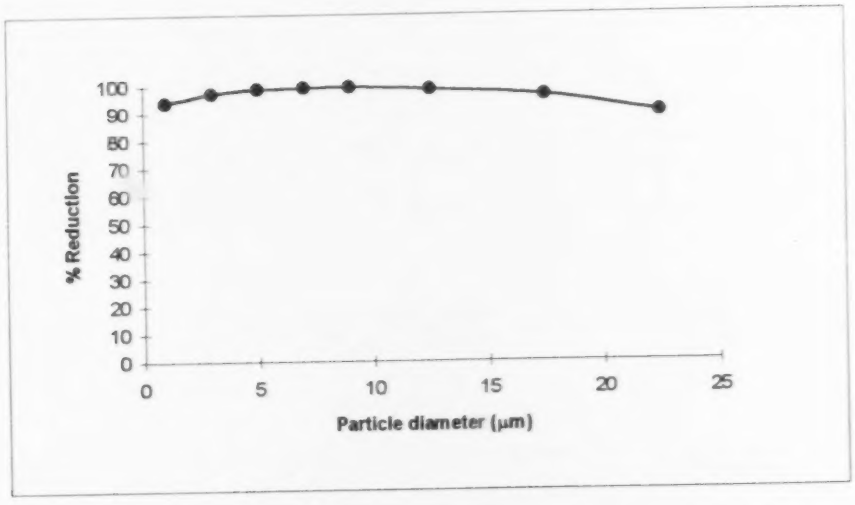


Fig. 4.6.5. Percent reduction of volume concentration after flocculation (10 min) and after DAF (20 min) at 100 rpm

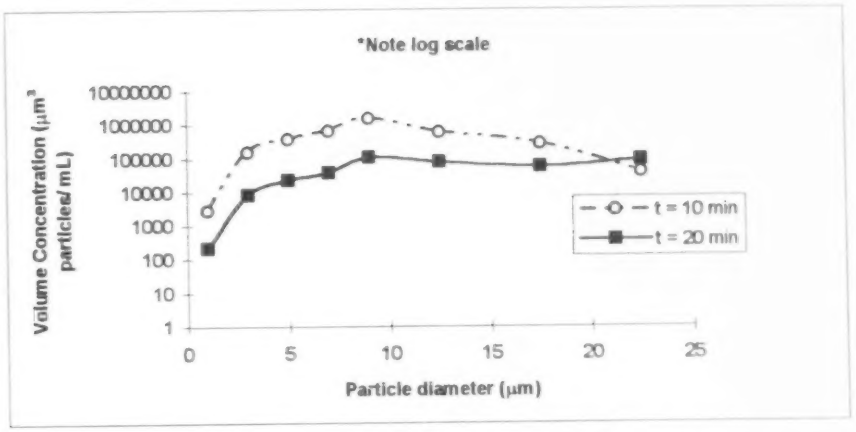


Fig. 4.6.6. Volume concentration of particles after flocculation (10 min) and after DAF (20 min) at 300 rpm

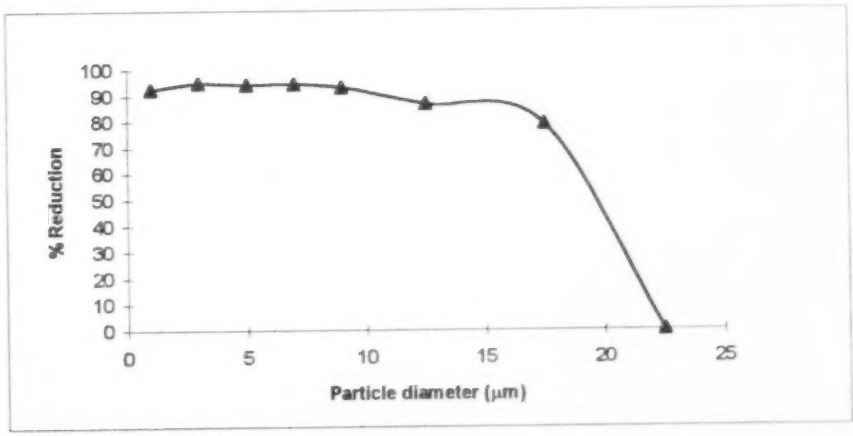


Fig. 4.6.7. Percent reduction of volume concentration from after flocculation (10 min) to after DAF (20 min) at 300 rpm

concentration. The volume concentration of particles at this size range after flocculation was significantly less than at the other mixing intensities which could be explained by the higher shear on the particles during flocculation at 300 rpm. The increase in the volume concentration at this size range after DAF treatment could be a result of particles aggregating during DAF due to the turbulence caused by DAF treatment. Therefore, more particles would be found in this size range after DAF than before DAF. The optimum removal occurred for flocculation at 300 rpm in the size range from 3 to 7 μm. This smaller optimal size range may have been the result of the high shear experienced during mixing at 300 rpm. Exactly the same results are found in the number concentration distributions for the three flocculation mixing intensities (Fig. 4.6.8 to 4.6.13).

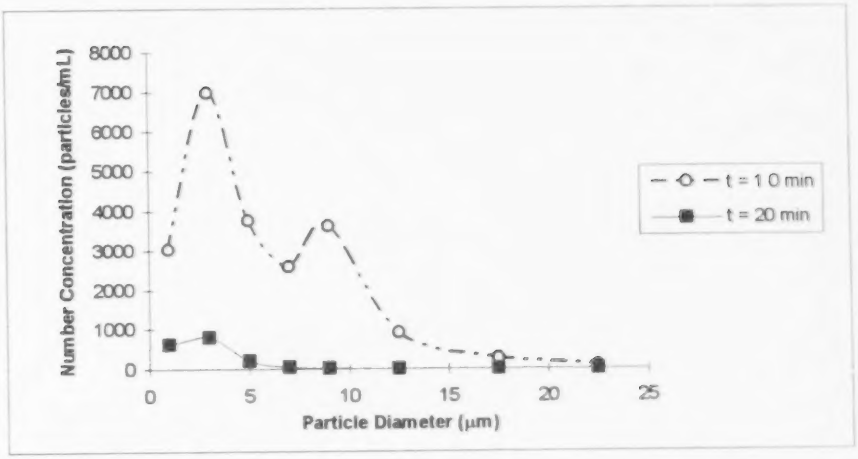


Fig. 4.6.8. Number concentration distributions after flocculation (10 min) and after DAF (20 min) at 60 rpm

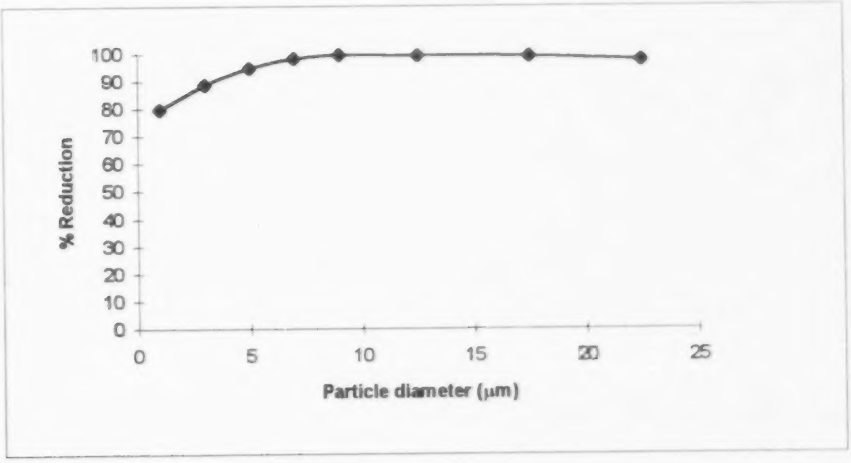


Fig. 4.6.9. Percent reduction in number concentration from after flocculation (10 min) to after DAF (20 min) at 60 rpm

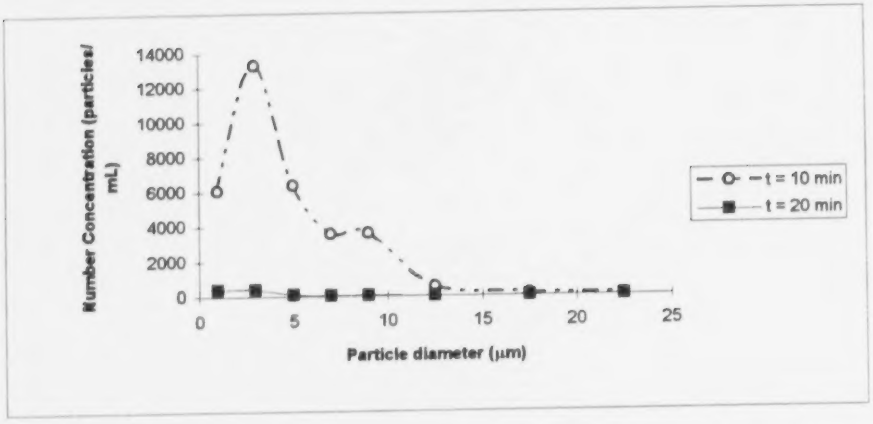


Fig. 4.6.10. Number concentration of particles from after flocculation (10 min) to after DAF (20 min) at 100 rpm

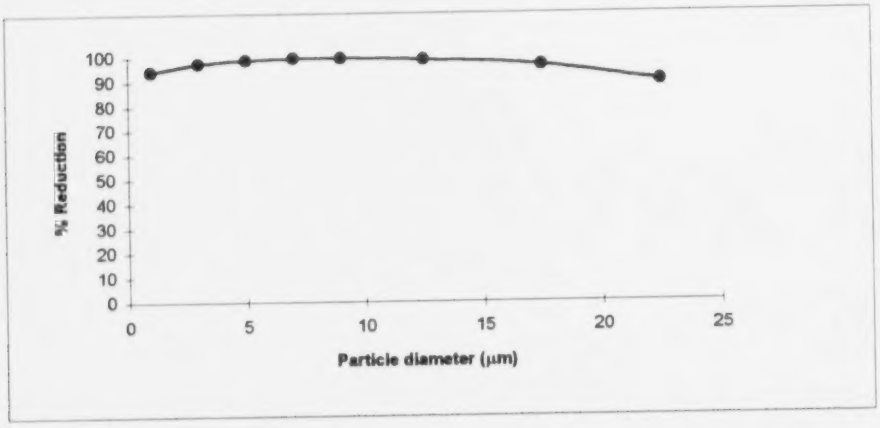


Fig. 4.6.11. Percent reduction of number concentration from after flocculation (10 min) to after DAF (20 min) at 100 rpm

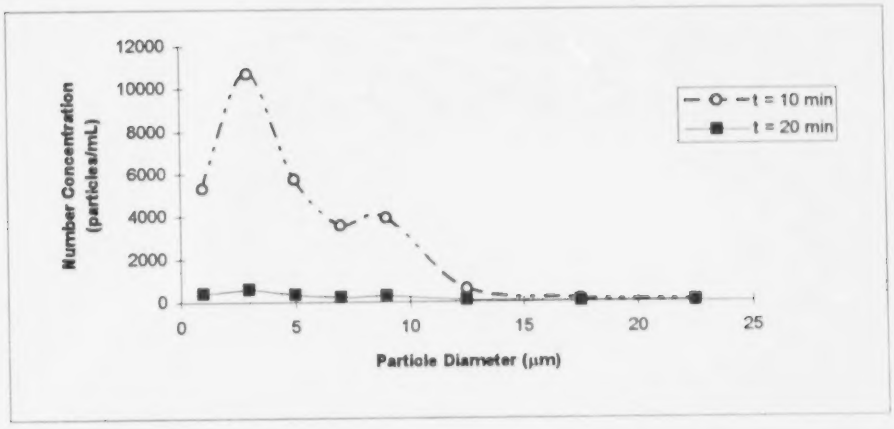


Fig. 4.6.12. Number concentration of particles after flocculation (10 min) and after DAF (20 min) at 300 rpm

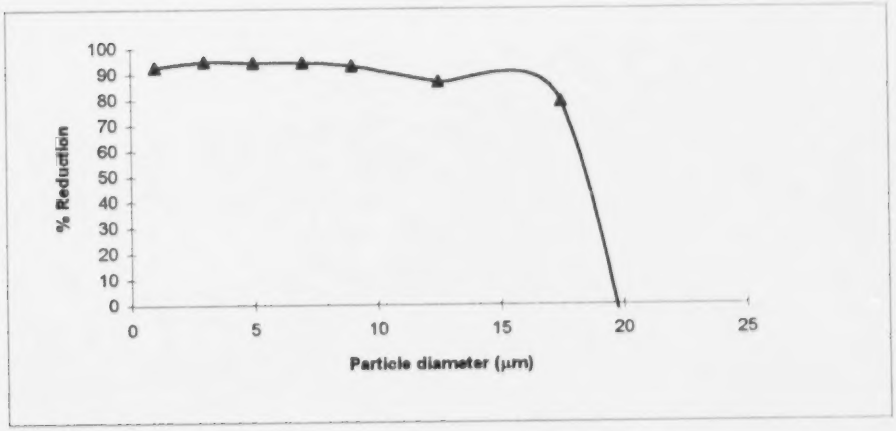


Fig. 4.6.13. Percent reduction of number concentration from after flocculation (10 min) to after DAF at 300 rpm

From the previous data, a clearer picture of the relationship between particle size distribution and DAF performance is forming. In general, DAF seems to remove particles best the in the range between 7 and 12.5 μm, with the exception of very high flocculation mixing intensities where shear effects may come into play as hypothesized before. However, it must be emphasized that these results are mainly a comparison between particles size distributions as controlled by flocculation time and mixing intensity. To evaluate graphically the effect of flocculation mixing intensity at 10 minutes (just before DAF) on particle size distribution, we can plot the same volume and number concentration distributions as above, comparing particle size distribution in raw water (before flocculation) to that of flocculation after 10 minutes. It is interesting with the varying sizes for removal found above, that the volume and number concentration distributions for all three mixing intensities are very similar (Fig. 4.6.14 to 4.6.25). All show a reduction in volume and number concentration of particles in the size ranges up to and including 7 μm in the 10 minutes of flocculation. Above 7 μm, there is an increase in the number and volume of particles to a maximum in each experiment at approximately 13 μm. Above 13 μm there is still an increase in the volume and number concentration, but less than at the maximum. It is interesting to note that the maximum volume and number concentrations of particles produced at these mixing intensities after 10 minutes seem to be outside the size range of maximum removal of particles by DAF. It is possible that this is seen with this data due to a limited number of sampling channels and subsequently large channel widths in the particle counter.

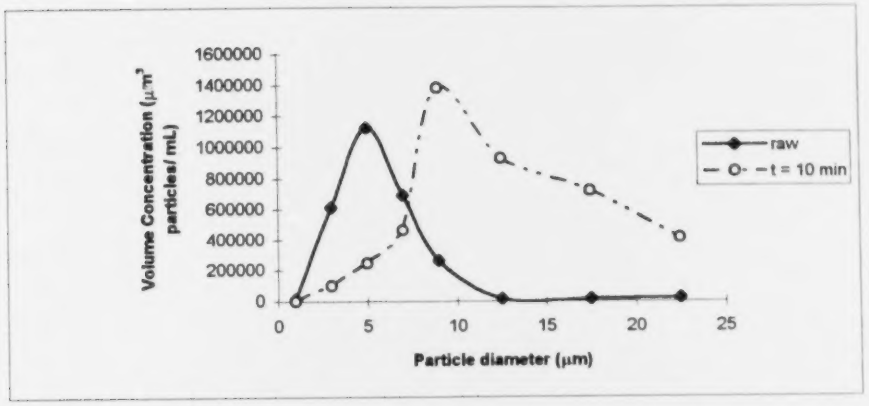


Fig.4.6.14. Volume concentration of particles for raw water and after flocculation at 60 rpm

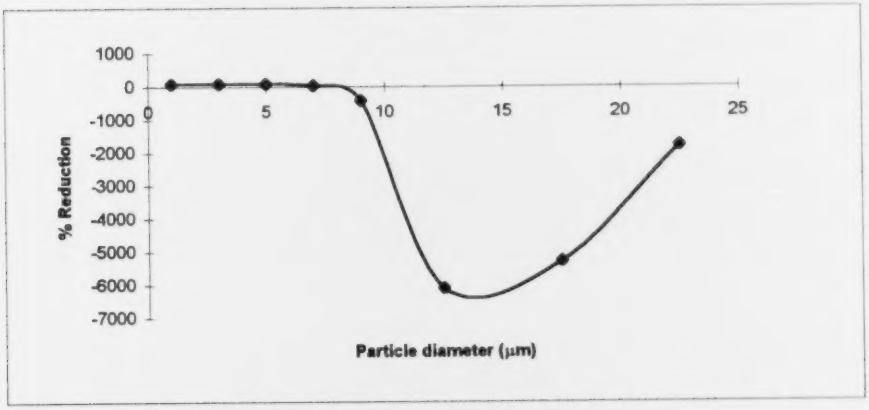


Fig.4.6.15. Percent reduction in volume concentration from raw water and after flocculation (10 min) at 60 rpm

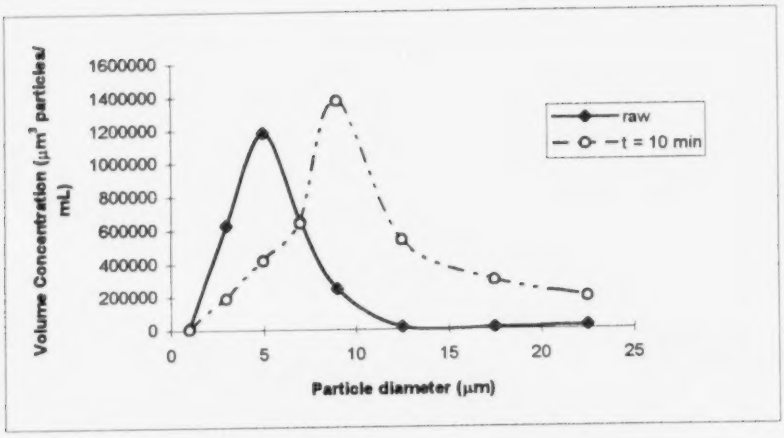


Fig. 4.6.16. Volume concentration of particles for raw water and after flocculation (10 min) at 100 rpm

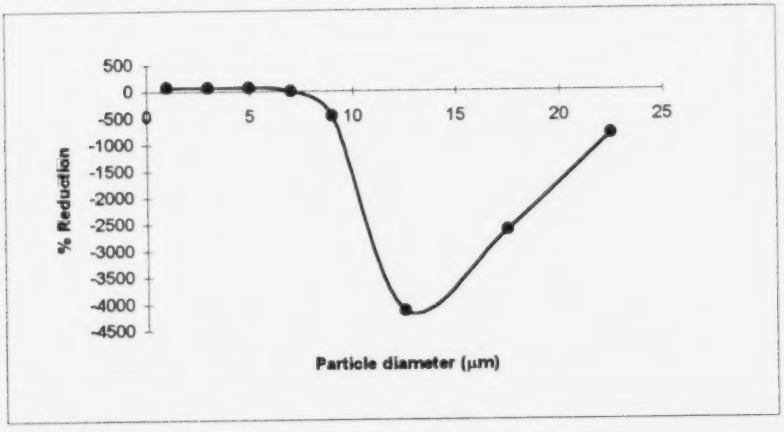


Fig. 4.6.17. Percent reduction in volume concentration from raw water to after flocculation (10 min) at 100 rpm

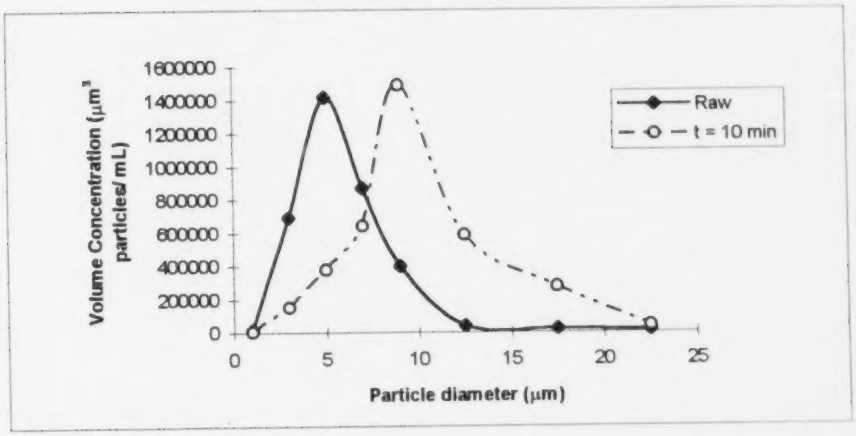


Fig. 4.6.18. Volume concentration of particles for raw water and after flocculation (10 min) at 300 rpm

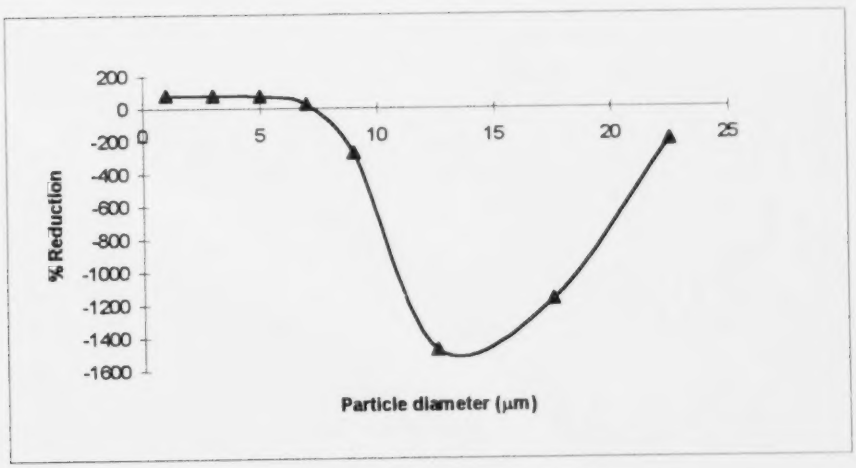


Fig. 4.6.19. Percent reduction in volume concentration from raw water to after flocculation (10 min) at 300 rpm

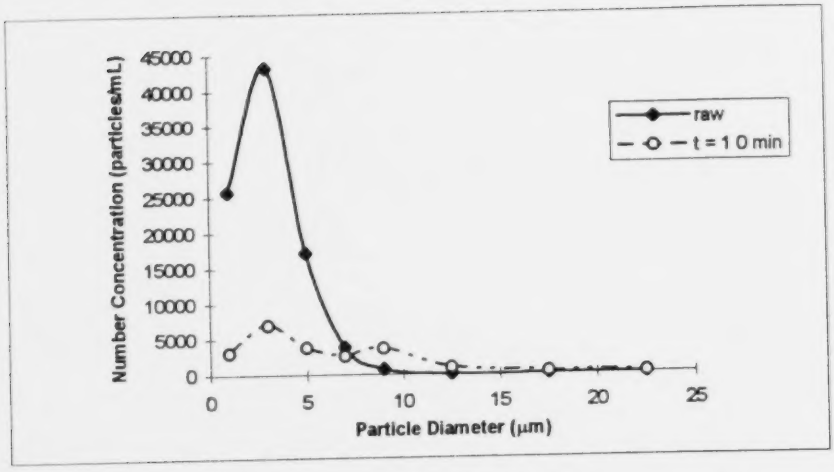


Fig. 4.6.20. Number concentration distribution for raw water and after flocculation (10 min) at 60 rpm

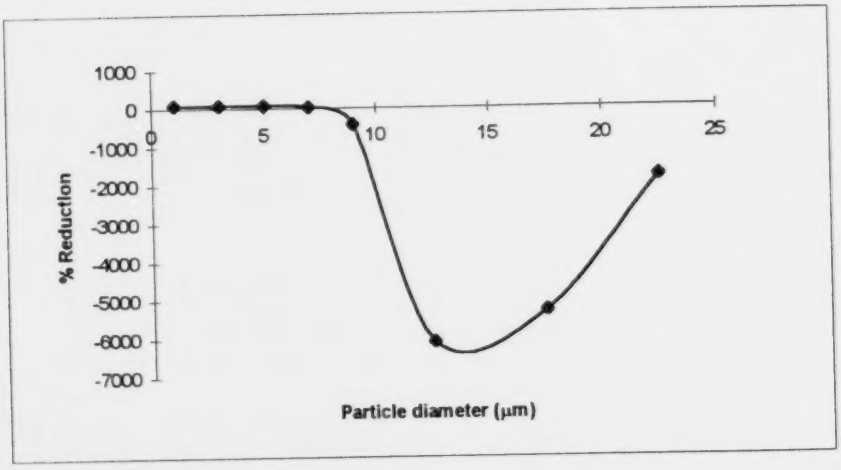


Fig. 4.6.21. Percent reduction of number concentration from raw water to after flocculation (10 min) for 60 rpm

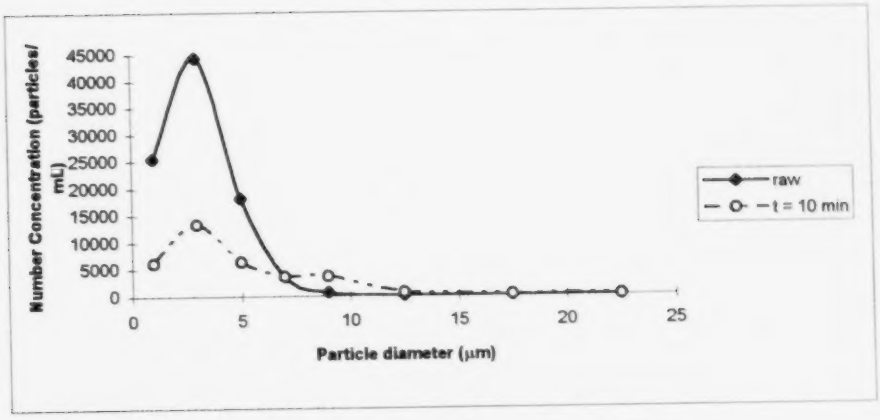


Fig. 4.6.22. Number concentration of particles for raw water and after flocculation (10 min) at 100 rpm

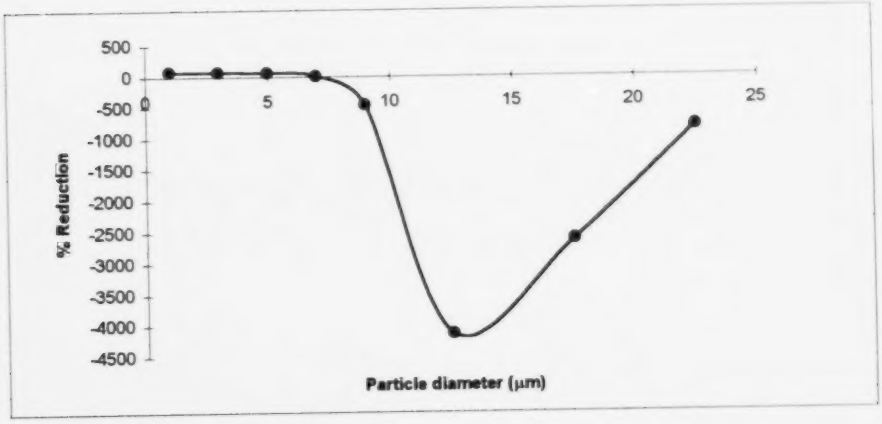


Fig. 4.6.23. Percent reduction in number concentration from raw water after flocculation (10 min) at 100 rpm

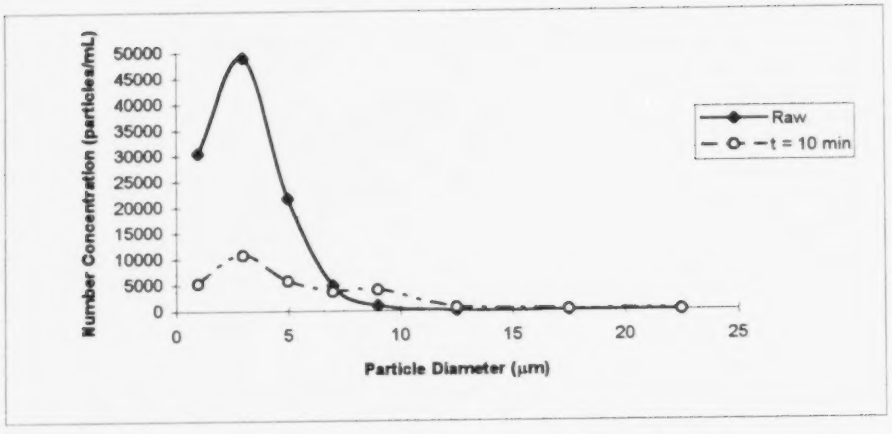


Fig.4.6.24. Number concentration of particles for raw water and after flocculation (10 min) at 300 rpm

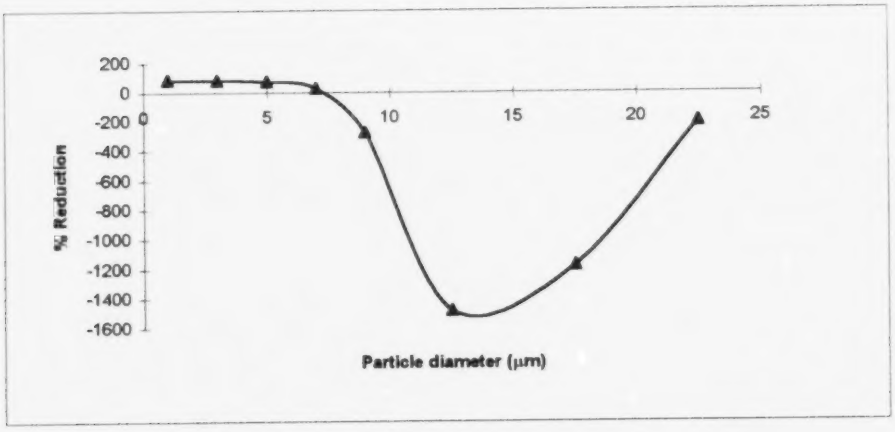


Fig. 4.6.25. Percent reduction in number concentration from raw water to after flocculation (10 min) at 300 rpm

A general trend in the particle size distribution function can be seen using the power law. The particle size distribution function is defined as the differential number concentration of particles (ΔN) within a certain size interval (Δd_p) divided by that size interval (Lawler et al., 1983). The power law states that the number of particles per size category or size distribution function ($\Delta N/\Delta d_p$) is an inverse power function of the size of the particle (d_p). In equation form, this is:

$$\Delta N/\Delta d_p = A\, d_p^{-\beta}$$

and taking the log of both sides:

$$\log (\Delta N/\Delta d_p) = \log (A) - \beta \log (d_p)$$

Plotting $\log (\Delta N/\Delta d_p)$ vs. $\log (d_p)$ should give a straight line with slope β and intercept log (A). The intercept (log (A)) is related to the concentration of particles in suspension. The slope (β) is an indicator of the relative distribution of number concentration of particles as a function of particle size (Lawler et al., 1983). Generally a steep slope indicates that there are relatively higher concentrations of smaller particles (Wilczak et al., 1992). The slope obtained from the power law does not give a numerical size range of the particle size distribution or a removal efficiency. Rather it gives an indication of the relative size range where the highest number concentration of particles can be found. Therefore, when interpreting the descriptors "smaller" and "larger" with regards to particle sizes, it must be remembered that particles were measured in the size range of 1 to 25 μm. The plots of the particle size distributions via the power law for raw

water, after flocculation, and after DAF for each flocculation mixing intensity are shown in Fig. 4.6.26.

It was possible to do a linear regression analysis to find the slope of the lines. The correlation coefficients (R^2) are listed in Table 4.6.1 along with the log A and β values for the samples of raw water, after flocculation, and after DAF for each mixing intensity.

Table 4.6.1 Summary of R^2, β and log A values for all mixing intensities for raw water, after flocculation, and after DAF

	Raw			After Flocculation			After DAF		
	R^2	β	Log A	R^2	β	Log A	R^2	β	Log A
60 RPM	0.84	4.41	5.6	0.81	2.14	4.09	0.93	3.18	3.38
100 RPM	0.84	4.46	5.62	0.82	2.72	4.57	0.96	2.76	2.95
300 RPM	0.84	4.41	5.72	0.76	2.92	4.62	0.88	2.12	3.06

The correlation coefficients show that the lines are straight enough that the slope and intercept can be viewed with confidence. The intercepts, although rarely used to interpret data, are included in Table 4.6.1 for interest. From the slope of the lines, it is evident that the particle size distributions of the raw waters were essentially the same. At 60 rpm, the particle size distribution shifted from a high concentration of relatively small particles to a high concentration of relatively large particles during flocculation, shown by a shallowing of the slope. This result is to be expected during flocculation at low mixing intensities.

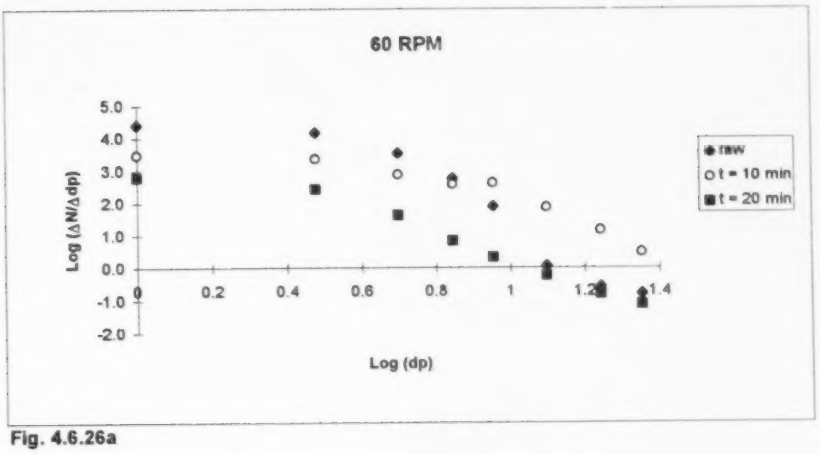


Fig. 4.6.26a

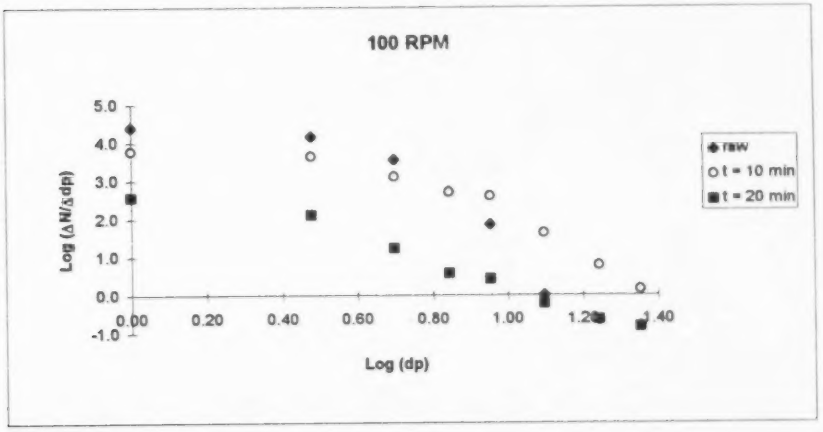


Fig.4.6.26b

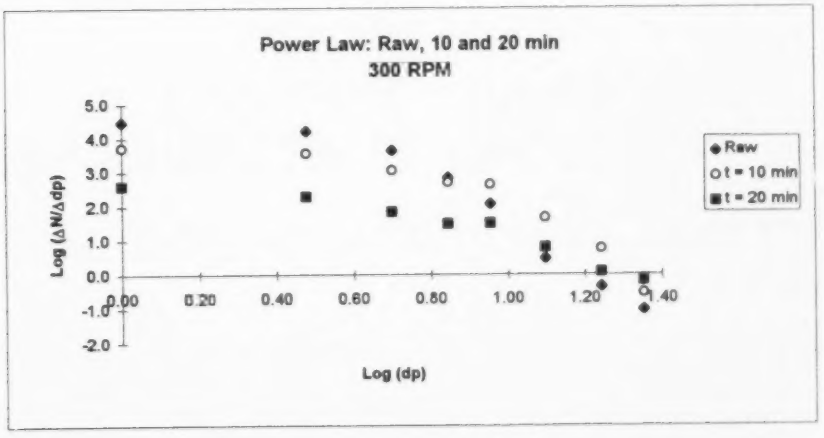


Fig. 4.6.26c

Fig.4.6.26a,b,c. Power law plots of particle size distributions for raw water, after flocculation (10 min) and after DAF (20 min) for each of a) 60, b) 100 and c) 300 rpm.

During DAF, the particle size distribution shifted again to higher concentrations of smaller particles, although not as much so as in the raw water, suggesting that the smaller particles were not as well removed by DAF. These results corroborate those found in Figures 4.6.20-21. At 100 and 300 rpm, the particle size distribution again shifted from a high concentration of relatively small particles to relatively larger particles during flocculation. After DAF for the 100 rpm sample, the particle size distribution did not change that much, suggesting that the larger particles were not removed as effectively. This phenomenon was shown in Fig. 4.6.23, the percent removal of particles as number concentration. The β value for 300 was seen to decrease after DAF suggesting a higher concentration of larger particles. This may have been the result flocculation during DAF as mentioned previously and seen in Fig. 4.6.25. The power law plots correlated well with the plots of number concentration distributions and gave a numerical value to the observed results.

To further understand the effect of flocculation mixing intensity and time on the particle size distribution, it is necessary to examine time trend data. Figures 4.6.27 to 4.6.32 show the change in number and volume of particles in each size range over time as a percent of the total number or volume of particles in the raw water. This was useful as it gave a breakdown of the trends in volume and number concentration in each size range over the time of flocculation for each flocculation mixing intensity. The trends for the larger size ranges are difficult to determine since the percent of the total volume or number concentration is very low. However, the general trends for the majority of the size ranges can be seen and are similar for all flocculation mixing intensities. In general, the particles smaller than 8 μm decrease in concentration up to 7 minutes, after which the concentrations increase slightly. The particles 8 μm and larger show an opposite trend, increasing in concentration up to 7 minutes and decreasing slightly thereafter. This phenomenon after 7 minutes can be explained by over-mixing of the solutions causing floc break-up and suggests further investigation of shorter flocculation times.

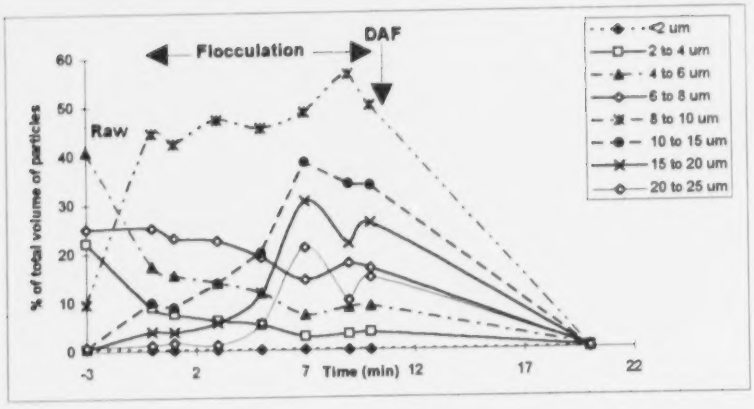


Fig.4.6.27. Change in volume of particles in each size range over time at 60 rpm as a percent of the total volume concentration of raw water

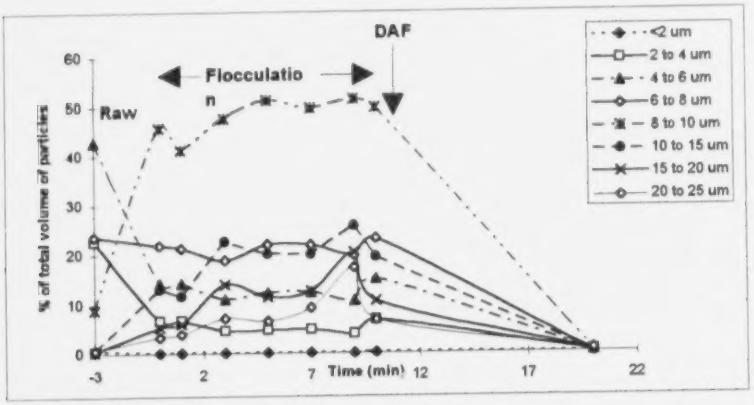


Fig.4.6.28. Change in volume of particles in each size range over time at 100 rpm as a percent of the total volume concentration of raw water

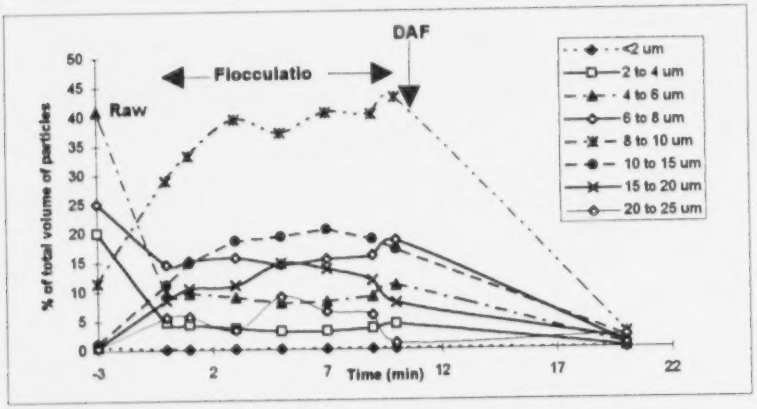


Fig.4.6.29. Change in volume of particles in each size range over time at 300 rpm as a percent of the total volume concentration of raw water

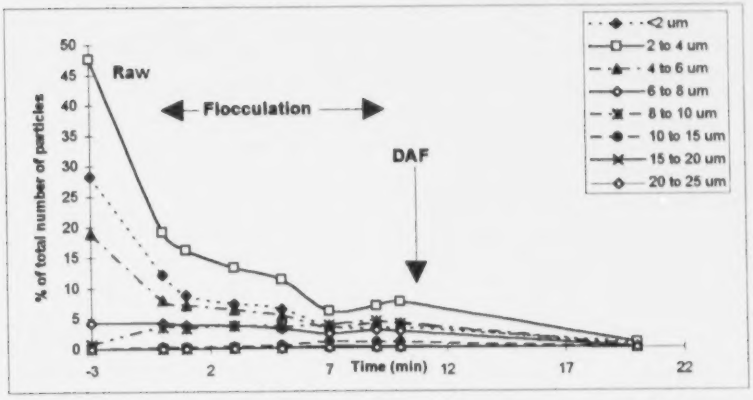


Fig.4.6.30. Change in number of particles in each size range over time at 60 rpm as a percent of the total number concentration of raw water

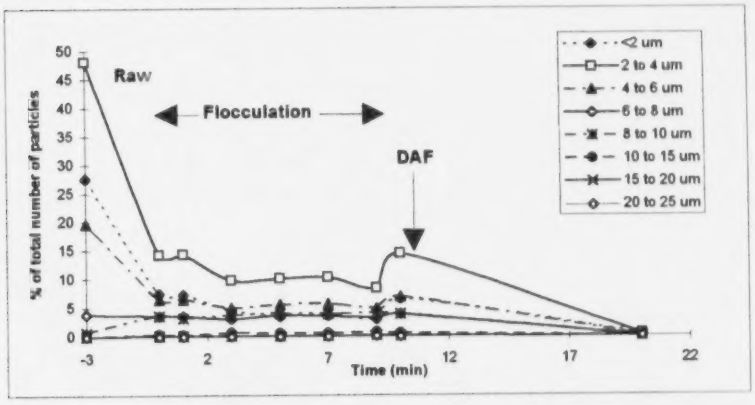


Fig.4.6.31. Change in number of particles in each size range over time at 100 rpm as a percent of the total number concentration of raw water

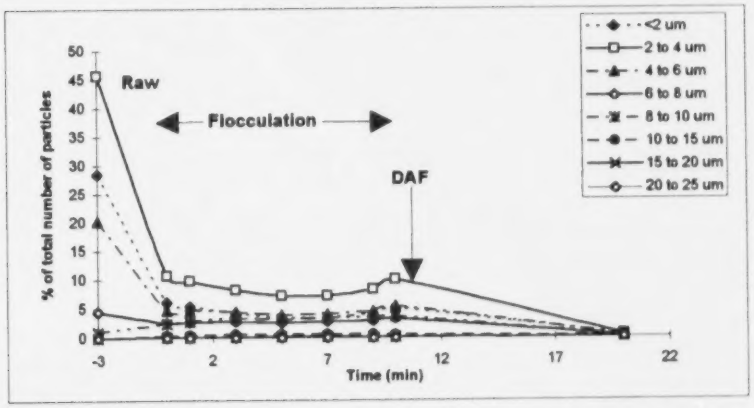


Fig.4.6.32. Change in number of particles in each size range over time at 300 rpm as a percent of the total number concentration of raw water

It is interesting to note that neither the number concentration nor the volume concentration remain constant throughout flocculation (Fig. 4.6.33 and 4.6.34). It is expected by the very nature of flocculation that the number of particles will decrease as smaller particles join to create larger particles. That the number of particles increases after a certain amount of flocculation could be the result of shear as mentioned previously. It would be cost-effective in this case to examine the particle size distribution and DAF performance at earlier flocculation times to see if comparable results are obtained. An interesting problem is posed by the change in volume concentration. A change in volume suggests that either the mass or the density of the flocs changed. While the mass may have increased slightly due to the addition of coagulant, it is unlikely that this would account for, in some cases, a 60% increase in volume. A more reasonable explanation would be that the volume of the flocs changed during flocculation due to water being trapped in the flocs. The total volume of the flocs increased with time to a certain point and then decreased due perhaps to floc break-up causing water to be "lost" from the flocs. We would expect that higher flocculation mixing intensities would result in smaller increases in volume as shear forces keep the flocs small. This can be seen in Fig. 4.6.34. These effects should not affect the presentation of results as individual distributions and percent changes are presented and total volume or number changes are not factors.

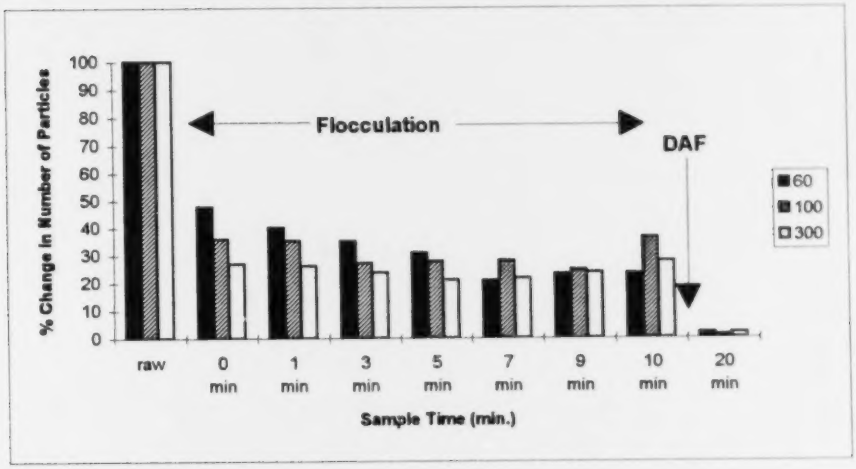


Fig. 4.6.33. Change in number concentration of particles with repect to the number concentration of particles in raw water

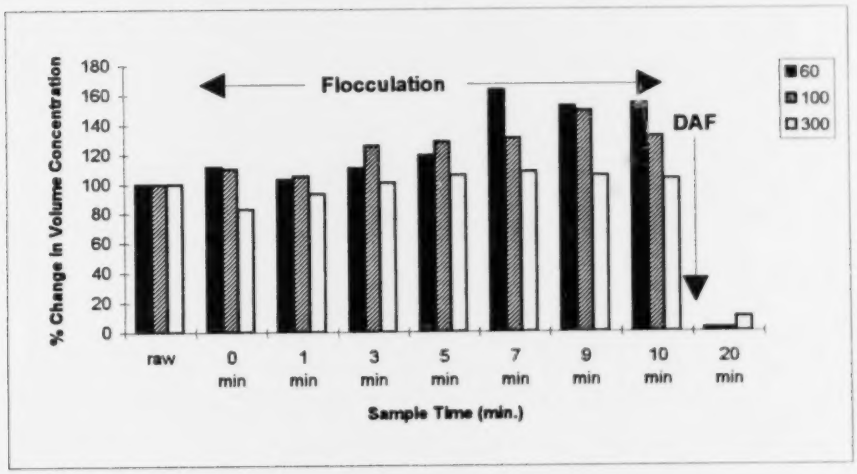


Fig. 4.6.34. Change in volume concentration of particles with repect to the volume concentration of particles in raw water

4.6.1 Limitations of Experiment

It is difficult to determine the optimum flocculation intensity and particle size distribution from this experiment. It would be necessary to investigate the effect of various particles size distributions by varying the flocculation time for each mixing intensity. This could be done as a cost-saving measure for a full-scale plant, since it is probable that a shorter flocculation time would produce a better particle size distribution.

In collecting data for this analysis, there were many sources of error. There was the possibility of floc break-up when the samples were taken from the mixing jars, diluted, mixed, and analyzed in the particle counter. To decrease this source of error, all solutions were handled gently and a 0.6% Isotone solution was added to prevent floc break-up in the particle counter. In addition, this source of error was common to all samples and should therefore affect all results similarly. There was also the possibility of an increase in floc size as the samples could not be diluted and mixed immediately and the flocs may have settled. To negate this error, as series of experiments should have been done to determine the effect of settling time on particle size distribution. Unfortunately, this was not done due to time limitations. However, the time the solutions were left standing was minimal and similar for each sample, so it is believed that this did not drastically affect the experimental results. Although every effort was made to prevent these errors, it is almost certain that some error was introduced. Much of this error could be avoided by in-situ measurement of the particle size distribution.

5. CONCLUSIONS

The experiments and analysis in this study yielded a number of conclusions and each of the research objectives were met.

Eight coagulants were screened for their effectiveness with DAF and their doses optimized. Of these eight, five were used in the statistical tests based on the results of DAF performance testing. Aluminum-based coagulants displayed better all-around performance than iron-based coagulants or organic polymers. The performance of organic polymers used as primary coagulants was found to be unsatisfactory, although the optimum dosages were considerably lower. It is likely that these organic polymers would perform well in conjunction with metal-based coagulants. However, combinations of polymers and coagulants were not investigated in this study. Ferifloc, an example of an iron-based coagulant, gave good reduction of organics. However, these results were often accompanied by poor reduction of or increase in turbidity and true colour. Aluminum-based coagulants with lower optimum doses are favoured because they produce lower aluminum residuals. In this study, NIAD-1 and PASS yielded the best treated water quality with the lowest aluminum residuals.

The correct dose of coagulant is necessary for good DAF treatment. Either over- or underdosing is likely to cause a deterioration in treated water quality. However, coagulant addition is necessary for effective DAF treatment since poor removal of the surrogate parameters occurred in the control jars to which no coagulant was added.

Pilot-plant studies revealed that increasing flocculation mixing intensity had an overall beneficial effect on treated water quality, while increasing flocculation mixing time had the opposite effect. The actual effects of either parameter were not very notable, however. It is possible that the high and low values tested were outside the range that would show an effect.

At the optimum coagulant dosages for both synthetic and natural water, the optimum flocculation mixing intensity (G) was at 100 rpm ($G = 60\ s^{-1}$). In both experiments, the quality of the treated water improved with increasing mixing intensity up to the optimum value, after which the treated water quality either decreased or showed no further improvement.

The investigation into the relationship between flocculation mixing intensity, particle size distribution and DAF performance revealed some interesting results. Higher flocculation mixing intensities produced more smaller particles and fewer larger particles than lower mixing intensities. This is thought to be a result of shear forces acting on the flocs during flocculation. Reduction of number and volume concentration occurred at every size range during DAF treatment with one exception. The volume and number concentrations of the largest particle size range increased during DAF, possibly because of flocculation occurring during DAF treatment. At lower flocculation mixing intensities, the maximum removal of particle volume and number concentration occurred in the 7 to 12.5 μm range.

General trends in particle size distribution were seen in all flocculation mixing intensities at 10 minutes of flocculation. Reduction of number and volume

concentration of particles of 3 μm and smaller was observed. Above 3 μm, the number and volume concentration increased to the 13 μm size range. Above this range, there was still an increase in the number and volume concentrations, but not as conspicuous as at 13 μm. This general trend was confirmed by using the power law and plotting log ($\Delta N/\Delta dp$) vs. log (dp). Number and volume concentrations were not constant throughout flocculation. This is not expected to bias the presentation of the data.

6. RECOMMENDATIONS

Due to the many constraints on the study, it was neither possible nor practical to evaluate all the parameters that could affect the performance of DAF treatment.

The effect of pH was not examined in this study. It is acknowledged that pH has an important effect on the chemical behaviour of the coagulant in the treatment process, and therefore on the effectiveness of DAF. Free aluminum residuals were quite high in these experiments, which is thought to be the result of alkaline pHs. The pH of the experiments was not controlled in order to simulate existing treatment plant conditions. However, this is an important parameter to consider, particularly with regards to the optimum dose of the coagulant and aluminum residuals.

Other parameters such as rapid mix time and intensity, DAF recycle rate, saturator pressure, DAF residence time and flocculation time were held constant. These parameters are expected to have an effect on the performance of DAF and as such should be investigated in future studies. Flocculation mixing time in particular was shown to have an effect on particle size distribution. It is thought that the flocculation time was too long in this experiment and resulted in over-flocculation. A better perspective on the relationship between particle size distribution and DAF performance may be seen with further investigation of flocculation mixing time.

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APPENDIX

ANALYTICAL DATA

Coagulant Screening

Experiment # 1

Coagulant Type: Alum
Coagulant Stock Solution Concentration (mg/L): 4.55×10^{4} as AL

Date: 6/20/95
Time: 5:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	50	100	150
Volume per 1 L (mL)		0	1.099	2.198	3.297
pH	8.01	8.01	7.32	6.92	6.54
Turbidity (NTU)	0.62	0.56	0.37	0.32	0.63
True Color (Pt-Co Units)	4	9	2	1	-
Temperature (°C)	12	14.5	14.5	14.5	14.5
DOC mg/L C	8.47	7.255	4.946	4.379	4.054
Chlorophyll-a (ug/L)	-	-	-	-	-

Experiment # 2

Coagulant Type: Alum
Coagulant Stock Solution Concentration (mg/L): 4.55×10^{4} as AL

Date: 6/21/95
Time: 9:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	50	100	150
Volume per 1 L (mL)		0	1.099	2.198	3.297
pH	7.87	7.92	7.27	6.82	6.5
Turbidity (NTU)	0.60	0.39	0.44	0.50	0.93
True Color (Pt-Co Units)	7	5	0	1	2
Temperature (°C)	10	13	13	13	13
DOC mg/L C	7.679	7.517	5.125	4.734	4.158
Chlorophyll-a (ug/L)	-	-	-	-	-

Coagulant Screening

Experiment # 3

Coagulant Type: Alum
Coagulant Stock Solution Concentration (mg/L): 4.55×10^4 as AL

Date: 8/1/95
Time: 4:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)	0	50	75	100	125
Volume per 1 L (mL)		1.099	1.648	2.198	2.747
pH	8.02	7.23	7.03	6.87	6.67
Turbidity (NTU)	1.00	0.90	0.65	0.71	0.87
True Color (Pt-Co Units)	12	2	3	2	1
Temperature (°C)	14	15	15	15	15
DOC mg/L C	6.079	2.761	2.89	2.545	2.622
Chlorophyll-a (ug/L)	1.06	0.25	0.00	0.00	0.00

Experiment # 4

Coagulant Type: Alum
Coagulant Stock Solution Concentration (mg/L): 4.55×10^4 as AL

Date: 8/1/95
Time: 6:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)	0	150			
Volume per 1 L (mL)		3.297			
pH	8.02	6.49			
Turbidity (NTU)	1.00	1.10			
True Color (Pt-Co Units)	12	2			
Temperature (°C)	14	15			
DOC mg/L C	6.079	1.639			
Chlorophyll-a (ug/L)	1.06	0.00			

Coagulant Screening

Experiment # 5

Coagulant Type: Alum
Coagulant Stock Solution Concentration (mg/L): 4.55×10^4 as AL

Date: 8/3/95
Time: 8:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)	0	0	60	70	80
Volume per 1 L (uL)		0	1317	1538	1758
pH	7.96	7.95	7.15	7.07	6.98
Turbidity (NTU)	0.95	0.90	0.75	0.70	0.83
True Color (Pt-Co Units)	11	10	7	9	6
Temperature (°C)	13.3	14	14	14	14.5
DOC mg/L C	5.177	4.373	3.271	3.385	2.765
Chlorophyll-a (ug/L)	1.38	1.19	0.29	0.22	0.21

Coagulant Screening

Experiment # 1

Coagulant Type: Chitosan
Coagulant Stock Solution Concentration (mg/L): 250

Date: 8/2/95
Time: 8:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	0.05	0.1	0.15
Volume per 1 L (mL)		0	200	400	600
pH	8.05	8.04	8	7.89	7.79
Turbidity (NTU)	1.2	1.0	1.0	1.0	1.1
True Color (Pt-Co Units)	8	8	5	5	6
Temperature (°C)	13	14	14	14.2	14
DOC mg/L C	6.94	5.00	6.57	6.44	8.19
Chlorophyll-a (mg/L)	1.90	1.73	1.67	1.86	1.73

Experiment # 2

Coagulant Type: Chitosan
Coagulant Stock Solution Concentration (mg/L): 250

Date: 8/2/95
Time: 10:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.2	0.4	0.6	0.8
Volume per 1 L (mL)		800	1600	2400	3200
pH	8.05	7.68	7.5	7.33	7.22
Turbidity (NTU)	1.2	1.1	1.0	1.1	1.0
True Color (Pt-Co Units)	8	6	5	4	4
Temperature (°C)	13	14.5	14.5	15	15
DOC mg/L C	6.94	7.69	10.38	12.45	15.81
Chlorophyll-a (mg/L)	1.90	1.71	1.67	1.48	1.70

Coagulant Screening

Experiment # 1

Coagulant Type: Ferifloc
Coagulant Stock Solution Concentration (mg/L): 1.2×10^4 as Fe^{+3}

Date: 6/29/95
Time: 8:30

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	10	20	30
Volume per 1 L (mL)			0.833	1.666	2.499
pH	8.06	8.13	3.42	3.25	3.27
Turbidity (NTU)	1.0	0.9	600.0	350.0	355.0
True Color (Pt-Co Units)	16	13	113	289	519
Temperature (°C)	12.5	13.8	13.8	13.8	13.8
DOC mg/L C	5.493	5.383	2.885	3.553	3.826
Chlorophyll-a (ug/L)	1.54	1.22	-	-	0.16

Experiment # 2

Coagulant Type: Ferifloc
Coagulant Stock Solution Concentration (mg/L): 1.2×10^4 as Fe^{+3}

Date: 7/18/95
Time: 13:00

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	5	10	15
Volume per 1 L (mL)			0.417	0.833	1.25
pH	8.04	8.04	4.86	3.43	3.33
Turbidity (NTU)	0.7	0.7	4.5	600.0	445.0
True Color (Pt-Co Units)	5	10	0	309	> 550
Temperature (°C)	16	17	16	16.5	16
DOC mg/L C	4.231	4.212	2.085	1.927	2.523
Chlorophyll-a (ug/L)	0.76	0.71	0.00	0.00	0.00

Coagulant Screening

Experiment #: 3

Coagulant Type: Ferifloc
Coagulant Stock Solution Concentration (mg/L): 1.2×10^4 as Fe^{+3} for jar#4; 1.2×10^2 as Fe^{+4} for jars 2&3

Date: 8/1/95
Time: 13:00

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	0.05	0.5	2
Volume per 1 L (uL)			417	4166	167 mL
pH	8.02	8.02	7.96	7.74	6.82
Turbidity (NTU)	1.0	1.0	1.6	1.5	1.0
True Color (Pt-Co Units)	12	8	6	9	0
Temperature (°C)	14	14	14	14	14
DOC mg/L C	6.079	5.02	5.087	3.909	3.016
Chlorophyll-a (ug/L)	1.06	1.10	1.02	0.49	0.14

Experiment #: 4

Coagulant Type: Ferifloc
Coagulant Stock Solution Concentration (mg/L): 1.2×10^4 as Fe^{+3}

Date: 8/1/95
Time: 18:00

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		2	3	4	
Volume per 1 L (uL)		417	4166	167 mL	
pH	8.02	6.73	6.47	5.71	
Turbidity (NTU)	1.0	0.9	1.0	1.5	
True Color (Pt-Co Units)	12	3	3	-	
Temperature (°C)	14	15.5	15.5	15.5	
DOC mg/L C	6.079	2.109	1.545	1.216	
Chlorophyll-a (ug/L)	1.06	0.08	0.00	0.00	

Coagulant Screening

Experiment # 1

Coagulant Type: Magnifloc 572C
Coagulant Stock Solution Concentration (mg/L): 143 mg/L

Date: 8/2/95
Time: 2:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.01	0.02	0.03	0.04
Volume per 1 L (mL)		70	140	210	280
pH	8.05	8.07	8.13	8.13	8.13
Turbidity (NTU)	1.2	1.1	1.1	1.1	1.0
True Color (Pt-Co Units)	8	6	6	7	10
Temperature (°C)	13	15.5	15.5	15.5	15.5
DOC mg/L C	6.94	5.15	4.79	4.65	6.22
Chlorophyll-a (ug/L)	1.90	1.62	1.63	1.57	1.67

Experiment # 2

Coagulant Type: Magnifloc 572C
Coagulant Stock Solution Concentration (mg/L): 143 mg/L jars 1 &2

Date: 8/2/95
Time: 6:00PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.05	0.1		
Volume per 1 L (mL)		350	700		
pH	8.05	8.15	8.17		
Turbidity (NTU)	1.2	1.1	1.1		
True Color (Pt-Co Units)	8	10	7		
Temperature (°C)	13	16	16		
DOC mg/L C	6.94	4.50	5.18		
Chlorophyll-a (ug/L)	1.90	1.76	1.65		

Coagulant Screening

Experiment # 1

Coagulant Type: Mag.577C
Coagulant Stock Solution Concentration (mg/L): 147 mg/L

Date: 8/2/95
Time: 4:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.01	0.02	0.03	0.04
Volume per 1 L (mL)		68	136	204	272
pH	8.05	8.13	8.16	8.16	8.15
Turbidity (NTU)	1.20	1.10	1.10	1.00	0.95
True Color (Pt-Co Units)	8	12		10	7
Temperature (°C)	13	15.5	15.5	15.5	15.5
DOC mg/L C	6.94	5.21	5.44	4.86	6.14
Chlorophyll-a (ug/L)	1.90	1.60	1.60	1.70	1.71

Experiment # 2

Coagulant Type: Mag.577C
Coagulant Stock Solution Concentration (mg/L): 147 mg/L

Date: 8/2/95
Time: 6:00PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.05	0.1		
Volume per 1 L (mL)		340	680		
pH	8.05	8.16	8.16		
Turbidity (NTU)	1.20	1.00	1.00		
True Color (Pt-Co Units)	8	8	0		
Temperature (°C)	13	15.5	15.5		
DOC mg/L C	4.23	5.88	4.78		
Chlorophyll-a (ug/L)	1.90	1.67	1.78		

Coagulant Screening

Experiment 3

Coagulant Type: Mag.577C
Coagulant Stock Solution Concentration (mg/L): 147 mg/L

Date: 8/3/95
Time: 10:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.1	0.15	0.2	
Volume per 1 L (mL)		680	1020	1360	
pH	7.96	8.05	8.06	8.07	
Turbidity (NTU)	0.95	1.40	0.88	0.91	
True Color (Pt-Co Units)	11	11	8	9	
Temperature (°C)	13.3	15	15	15	
DOC mg/L C	5.18	5.18	4.23	4.62	
Chlorophyll-a (ug/L)	1.38	1.27	1.25	1.37	

Coagulant Screening

Experiment #: 1

Coagulant Type: NIAD-1
Coagulant Stock Solution Concentration (mg/L): 6.3×10^4 as Al

Date: 7/19/95
Time: 11:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	10	20	30
Volume per 1 L (uL)		0	159	318	477
pH	8.15	8.26	7.89	7.7	7.49
Turbidity (NTU)	1.10	1.00	0.65	0.55	0.41
True Color (Pt-Co Units)	5	6	3	5	1
Temperature (°C)	15	19	18	18	18
DOC mg/L C	4.72	5.64	5.19	4.05	3.73
Chlorophyll-a (ug/L)	1.64	1.33	0.58	0.30	0.21

Experiment #: 2

Coagulant Type: NIAD-1
Coagulant Stock Solution Concentration (mg/L): 6.3×10^4 as Al

Date: 7/19/95
Time: 1:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		20	30	40	50
Volume per 1 L (uL)		318	477	636	795
pH	8.15	7.8	7.64	7.42	7.31
Turbidity (NTU)	1.10	0.60	0.55	0.41	0.44
True Color (Pt-Co Units)	5	2	0	0	0
Temperature (°C)	15	19	19	19	18
DOC mg/L C	4.72	3.82	3.76	4.27	4.23
Chlorophyll-a (ug/L)	1.64	0.44	0.23	0.04	0.00

Coagulant Screening

Experiment # 1

Coagulant Type: PACl
Coagulant Stock Solution Concentration (mg/L): 7.7×10^4 as Al

Date: 6/28/95
Time: 1:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	10	20	30
Volume per 1 L (uL)		0	130	260	390
pH	7.85	8.03	7.97	7.88	7.83
Turbidity (NTU)	0.78	0.75	0.70	0.72	0.59
True Color (Pt-Co Units)	2	2	1	1	1
Temperature (°C)	11.8	15	15	15	15
DOC mg/L C	5.84	5.77	5.48	4.98	4.45
Chlorophyll-a (ug/L)	13.33	8.38	9.14	7.62	6.48

Experiment # 2

Coagulant Type: PACl
Coagulant Stock Solution Concentration (mg/L): 7.7×10^4 as Al

Date: 6/28/95
Time: 4:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		20	30	40	50
Volume per 1 L (uL)		260	390	520	650
pH	7.85	7.97	7.95	7.74	7.67
Turbidity (NTU)	0.78	0.68	0.60	0.65	0.63
True Color (Pt-Co Units)	2	6	1	1	1
Temperature (°C)	11.8	15	15	15	15
DOC mg/L C	5.84	4.85	4.73	4.55	4.49
Chlorophyll-a (ug/L)	13.33	7.62	6.67	5.71	5.33

Coagulant Screening

Experiment #: 3

Coagulant Type: PACl
Coagulant Stock Solution Concentration (mg/L): 7.7×10^4 as Al

Date: 7/20/95
Time: 8:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		30	40	50	60
Volume per 1 L (uL)		390	520	650	780
pH	7.99	7.82	7.75	7.7	7.64
Turbidity (NTU)	0.77	0.75	0.73	0.70	0.65
True Color (Pt-Co Units)	9	3	1	1	3
Temperature (°C)	13	15	15	15	15
DOC mg/L C	6.61	5.49	4.70	4.92	5.09
Chlorophyll-a (ug/L)	11.22	6.86	7.24	4.67	5.29

Coagulant Screening

Experiment #: 1

Coagulant Type: PASS
Coagulant Stock Solution Concentration (mg/L): 8.7×10^4 as Al

Date: 6/29/95
Time: 12:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		10	20	30	40
Volume per 1 L (uL)		115	230	345	460
pH	8.06	7.42	7.26	6.91	6.82
Turbidity (NTU)	1.00	0.91	0.55	0.55	0.93
True Color (Pt-Co Units)	16	2	1	3	2
Temperature (°C)	12.5	16	15.1	16	16
DOC mg/L C	5.49	4.11	3.01	2.82	2.61
Chlorophyll-a (ug/L)	1.54	0.21	0.11	-	-

Experiment #: 2

Coagulant Type: PASS
Coagulant Stock Solution Concentration (mg/L): 8.7×10^4 as Al

Date: 7/18/95
Time: 3:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		10	20	30	40
Volume per 1 L (uL)		115	230	345	460
pH	8.04	7.55	7.39	6.97	6.79
Turbidity (NTU)	0.66	0.40	0.30	-	0.70
True Color (Pt-Co Units)	5	5	0	0	0
Temperature (°C)	15	18	18	17	17
DOC mg/L C	4.23	1.99	2.60	2.32	2.13
Chlorophyll-a (ug/L)	0.76	0.14	0.00	0.00	0.00

Coagulant Screening

Experiment #: 3

Coagulant Type: PASS
Coagulant Stock Solution Concentration (mg/L): 8.7×10^4 as Al

Date: 7/18/95
Time: 5:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		5	10	15	20
Volume per 1 L (uL)		58	115	173	230
pH	8.04	7.63	7.64	7.32	7.14
Turbidity (NTU)	0.66	0.65	0.45	0.50	0.63
True Color (Pt-Co Units)	5	2	2	3	0
Temperature (°C)	15	18	18	18	18
DOC mg/L C	4.23	2.62	2.50	2.95	2.77
Chlorophyll-a (ug/L)	0.76	0.12	0.07	0.00	0.00

Experiment #: 4

Coagulant Type: PASS
Coagulant Stock Solution Concentration (mg/L): 8.7×10^4 as Al

Date: 7/19/95
Time: 8:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		20	30	40	50
Volume per 1 L (uL)		230	345	460	575
pH	8.15	7.23	6.91	6.72	6.54
Turbidity (NTU)	1.10	0.35	0.40	0.60	1.10
True Color (Pt-Co Units)	5	1	0	0	0
Temperature (°C)	15	17	16	16	16
DOC mg/L C	4.72	2.72	2.02	2.24	1.91
Chlorophyll-a (ug/L)	1.64	0.00	0.00	0.00	0.00

Statistical Tests

Experiment # 1

Coagulant Type: Ferifloc
Coagulant Stock Solution Concentration (mg/L): 1.2×10^4 as Fe+3

Date: 8/22/95
Time: 6:30 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	2	2	2
Volume per 1 L (uL)		0	167	167	167
pH	8.01	8.02	6.57	6.58	6.63
Turbidity (NTU)	1.6	1.6	0.93	1.0	1.1
True Color (Pt-Co Units)	16	13	0	1	0
Temperature (°C)	15	16.2	16.2	16.2	16.2
DOC mg/L C	3.38	3.38	1.22	1.32	1.34
Chlorophyll-a (ug/L)	3.56	3.42	0.22	0.33	0.39

Statistical Tests

Experiment # 1

Coagulant Type: Mag.572C
Coagulant Stock Solution Concentration (mg/L): 143

Date: 8/23/95
Time: 8:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	0.01	0.01	0.01
Volume per 1 L (uL)		0	70	70	70
pH	8.04	8.04	8.05	8.06	8.06
Turbidity (NTU)	1.5	1.5	1.5	1.4	1.4
True Color (Pt-Co Units)	10	10	5	5	5
Temperature (°C)	14.5	15	15	15	15
DOC mg/L C	3.83	4.07	3.84	3.93	3.81
Chlorophyll-a (ug/L)	4.31	4.06	3.67	3.97	3.92

Statistical Tests

Experiment # 1

Coagulant Type: Mag.577C
Coagulant Stock Solution Concentration (mg/L): 147

Date: 8/23/95
Time: 11:00 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	0.1	0.1	0.1
Volume per 1 L (uL)		0	680	680	680
pH	8.04	8.07	8.07	8.07	8.07
Turbidity (NTU)	1.5	1.5	1.5	1.3	1.4
True Color (Pt-Co Units)	10	9	5	4	7
Temperature (°C)	14.5	15.2	15.5	15.5	15.5
DOC mg/L C	3.83	3.74	3.55	3.60	3.68
Chlorophyll-a (ug/L)	4.31	3.78	4.22	4.19	4.25

Statistical Tests

Experiment # 1

Coagulant Type: NIAD-1
Coagulant Stock Solution Concentration (mg/L): 6.3×10^4

Date: 8/22/95
Time: 4:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	30	30	30
Volume per 1 L (uL)		0	477	477	477
pH	8.01	8.03	7.35	7.33	7.32
Turbidity (NTU)	1.6	1.6	0.5	0.4	0.5
True Color (Pt-Co Units)	16	13	0	1	0
Temperature (°C)	15	16	16	16	16
DOC mg/L C	3.80	3.70	2.51	2.41	2.38
Chlorophyll-a (ug/L)	3.56	3.58	0.44	0.36	0.36
Al Residual (mg/L)	-	0	0.29	0.3	0.25

Statistical Tests

Experiment # 1

Coagulant Type: PASS
Coagulant Stock Solution Concentration (mg/L): 8.7×10^{4} as Al

Date: 8/22/95
Time: 1:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	30	30	30
Volume per 1 L (uL)		0	345	345	345
pH	8.01	8.02	6.78	6.74	6.74
Turbidity (NTU)	1.6	1.6	0.7	0.6	0.6
True Color (Pt-Co Units)	16	11	3	2	3
Temperature (°C)	15	15.5	15.5	15.8	16
DOC mg/L C	3.80	4.48	2.47	2.29	2.54
Chlorophyll-a (ug/L)	3.56	3.53	0.00	0.00	0.00
Al Residual (mg/L)	-	0	0.45	0.32	0.58

Pilot Plant Experiments

Optimum Dose Determination

Coagulant Type: NIAD-1 **Experiment #:** 1
Coagulant Stock Solution **Date:** 9/19/95
Concentration (mg/L): 6.3×10^4 **Time:** 4:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)	0	0	20	30	40
Volume per 1 L (uL)		0	317	477	635
pH	8..3	8.29	7.25	7.41	7.25
Turbidity (NTU)	0.55	0.54	0.35	0.27	0.35
True Color (Pt-Co Units)	4	3	2	0	0
Temperature (°C)	13	17	18	18	18

Coagulant Type: Ferifloc **Experiment #:** 1
Coagulant Stock Solution **Date:** 9/19/95
Concentration (mg/L): 1.9×10^4 as Fe+3 **Time:** 7:00 PM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	1.5	2	2.5
Volume per 1 L (uL)		0	79	105	132
pH	8.01	8.2	7.97	7.9	7.82
Turbidity (NTU)	0.62	0.46	0.78	0.72	0.78
Temperature (°C)	12	18.8	19	19	19

Coagulant Type: Ferifloc **Experiment #:** 2
Coagulant Stock Solution **Date:** 9/20/95
Concentration (mg/L): 1.9×10^4 as Fe+3 **Time:** 10:30 AM

Parameter	Raw Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	1.5	2	2.5
Volume per 1 L (uL)		0	79	105	132
pH	8.29	8.3	7.92	7.88	7.81
Turbidity (NTU)	0.46	0.51	1.10	0.90	1.00
True Color	13	5	9	8	5

Pilot-plant Experiments

		Experiment #:	1
Coagulant Type:	NIAD-1	**Date:**	9/19/95
Optimum Dose (mg/L)	6.3×10^4	**Time:**	

Parameter	Raw Water	DAF Effluent
pH	8.33	7.48
Turbidity (NTU)	0.55	0.33
True Color (Pt-Co Units)	4	3
Temperature (°C)	13.00	14.00
DOC mg/L C	4.517	2.623

Parameter	Exp. 1
G (s^{-1})	30
t_{floc} (min)	12
Q_{floc} (G/min)	11.1
Q_{DAF} (G/min)	5.6
% recycle	12
P_{sat} (psi)	70-71
DAF residence time (min)	18

Pilot-plant Experiments

		Experiment #:	2
Coagulant Type:	NIAD-1	**Date:**	9/20/95
Optimum Dose (mg/L	6.3×10^{4}	**Time:**	8:00 AM

Parameter	Raw Water	DAF Effluent
pH	8.29	7.56
Turbidity (NTU)	0.46	0.28
True Color (Pt-Co Units)	13	1
Temperature (°C)	13.00	14.00
DOC mg/L C	4.404	3.651

Parameter	Exp. 2
G (s^{-1})	30
t_{floc} (min)	24
Q_{floc} (G/min)	5.6
Q_{DAF} (G/min)	5.6
% recycle	11
P_{sat} (psi)	70-72
DAF residence time (min)	18.4

Pilot-plant Experiments

		Experiment #:	3
Coagulant Type:	NIAD-1	**Date:**	9/20/95
Optimum Dose (mg/L)	6.3×10^{4}	**Time:**	11:30 AM

Parameter	Raw Water	DAF Effluent
pH	8.29	7.41
Turbidity (NTU)	0.46	0.24
True Color (Pt-Co Units)	13	1
Temperature (°C)	13.00	14.00
DOC mg/L C	4.217	2.867

Parameter	Exp. 3
G (s^{-1})	70
t_{floc} (min)	24
Q_{floc} (G/min)	5.6
Q_{DAF} (G/min)	5.6
% recycle	11
P_{sat} (psi)	70-72
DAF residence time (min)	18.4

Pilot-plant Experiments

		Experiment #:	4
Coagulant Type:	NIAD-1	**Date:**	9/21/95
Optimum Dose (mg/L)	6.3×10^{4}	**Time:**	9:30 AM

Parameter	Raw Water	DAF Effluent
pH	8.13	7.4
Turbidity (NTU)	0.45	0.24
True Color (Pt-Co Units)	9	6
Temperature (°C)	13.00	14.00
DOC mg/L C	4.398	3.001

Parameter	Exp. 4
G (s^{-1})	70
t_{floc} (min)	12
Q_{floc} (G/min)	11.1
Q_{DAF} (G/min)	5.6
% recycle	11.3
P_{sat} (psi)	70-72
DAF residence time (min)	18

Flocculation Mixing - Synthetic Water

Optimization of coagulant dose

Experiment # 1

Coagulant Type: PACl

Coagulant Stock Solution Concentration (mg/L): 7.74×10^3 as Al

Date: 23/10/95

Time: 9:30 AM

Parameter	Raw Water AfterSpiking	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0	0.5	1.0	3.0
Volume per 1 L (uL)		0	650	1300	4000
pH (after pH adjustment)	5.52	5.50	5.45	5.52	5.58
Turbidity (NTU)	0.25	0.22	0.18	0.27	0.40
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL)	100000	79433	50119	79433	19953
Log N	5.000	4.900	4.700	4.900	4.300
EPM (um/sec/volt/cm)	-2.900	-2.900	-0.700	2.300	1.300

Flocculation Mixing - Synthetic Water

Optimization of coagulant dose

Experiment # 2

Coagulant Type: PACl

Date: 23/10/95

Coagulant Stock Solution Concentration (mg/L): 7.74×10^3 for jar #1

Time:

7.74×10^4 for jar #2,3 &4

Parameter	Raw Water AfterSpiking	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		3.0	10.0	20.0	30.0
Volume per 1 L (uL)		4000	130	260	390
pH (after pH adjustment)	5.52	5.50	5.52	5.47	5.50
Turbidity (NTU)	0.25	0.37	1.60	2.50	1.75
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL)	100000	19953	93325	234423	72444
Log N	5.000	4.300	4.970	5.370	4.860
EPM (um/sec/volt/cm)	-2.900	1.490	1.590	1.860	1.930

Flocculation Mixing - Synthetic Water

Optimization of coagulant dose

Experiment # 3

Coagulant Type: PACl
Coagulant Stock Solution Concentration (mg/L): 7.74×10^3

Date: 11/3/95
Time: 11:00 AM

Parameter	Raw Water AfterSpiking	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)		0.0	0.5	1.0	1.5
Volume per 1 L (uL)		0	65	130	194
pH (after pH adjustment)	7.38	5.57	5.47	5.47	5.45
Turbidity (NTU)	0.27	0.27	0.21	0.11	0.17
Temperature (°C)	21	21	21	21	21
Particle Concentration(#/mL) Log N	257107 5.410	310473 5.492	109147 5.038	35787 4.554	51600 4.713
EPM (um/sec/volt/cm)	-1.354	-1.096	0.698	0.862	0.774
Chlorophyll-a (ug/L)	6.889	5.899	2.286	0.254	0.175

Flocculation Mixing-Synthetic Water

Mixing intensity screening

Experiment #: 1
G=8 s^{-1} (N=20 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg Al/L) 7.74 x 10 3

Date: 11/19/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.40	5.5	5.53	5.52	5.56
Turbidity (NTU)	0.53	0.52	0.19	0.22	0.24
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	93079 4.969	112412 5.051	3428 3.535	1022 3.010	2026 3.307
Chlorophyll-a (ug/L)	7.38	4.77	1.59	1.43	1.65

Flocculation Mixing-Synthetic Water

Mixing intensity screening

Experiment #: 2
G=45 s^{-1} (N=80 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg Al/L) 7.74 x 10 3

Date: 11/19/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.40	5.48	5.55	5.51	5.46
Turbidity (NTU)	0.53	0.49	0.19	0.20	0.25
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	93079 4.995	98953 4.995	3157 3.499	2877 3.459	2038 3.309
Chlorophyll-a (ug/L)	7.38	5.67	0.46	0.35	0.29

Flocculation Mixing - Synthetic Water

Mixing intensity screening

Experiment #: 4
G=60 s^{-1} (N=100 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg Al/L) 7.74 x 10 3

Date: 12/5/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.42	5.47	5.42	5.58	5.43
Turbidity (NTU)	0.69	0.54	0.17	0.14	0.16
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	113309 5.054	68582 4.836	670 2.826	579 2.762	1621 3.210
Chlorophyll-a (ug/L)	10.67	9.55	0.33	0.37	0.22

Flocculation Mixing-Synthetic Water

Mixing intensity

Experiment #: 3
G=150 s^{-1} (N=200 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg Al/L) 7.74 x 10 3

Date: 11/19/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.40	5.57	5.58	5.43	5.48
Turbidity (NTU)	0.53	0.50	0.15	0.18	0.16
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	93079 4.969	- -	1284 3.109	1664 3.221	870 2.940
Chlorophyll-a (ug/L)	7.38	5.49	0.00	0.00	0.00

Flocculation Mixing-Synthetic Water

Mixing intensity screening

Experiment #: 7
G=150 s^{-1} (N=200 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg Al/L) 7.74 x 10 3

Date: 11/19/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.42	5.53	5.52	5.48	5.5
Turbidity (NTU)	0.69	0.55	0.14	0.18	0.11
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	113309 5.054	65475 -	747 2.873	285 2.455	353 2.548
Chlorophyll-a (ug/L)	10.67	10.36	0.13	0.06	0.02

Flocculation Mixing-Synthetic Water

Mixing intensity screening

Experiment #: 5
G=250 s^{-1} (N=300 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
ACl stock soln. conc. (mg Al/L 7.74 x 10 3

Date: 12/5/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.42	5.47	5.52	5.52	5.45
Turbidity (NTU)	0.69	0.56	0.13	0.16	0.11
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	113309 5.054	88437 4.947	150 2.175	157 2.196	711 2.852
Chlorophyll-a (ug/L)	10.67	10.67	0.21	0.08	0.02

Flocculation Mixing-Synthetic Water

Mixing intensity screening

Experiment #: 6
G=350 s^{-1} (N=400 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
ACl stock soln. conc. (mg Al/L 7.74 x 10 3

Date: 12/5/95

Parameter	Spiked Water	Jar # 1	Jar # 2	Jar # 3	Jar # 4
pH (pH after adjustment)	7.42	5.55	5.52	5.5	5.5
Turbidity (NTU)	0.69	0.52	0.13	0.30	0.13
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL) Log N	113309 5.054	81778 4.913	470 2.672	156.5 2.195	67.5 1.829
Chlorophyll-a (ug/L)	10.67	10.72	0.41	0.29	0.14

Example of EPM Measurements

Flocculation Mixing-Synthetic Water

Experiment # 3
Date 11/3/95

Reading #	Raw Water Volt= 60 Temp= 22 pH= 7.38		Jar #1 Volt= 60 Temp= 22 pH= 5.57		Jar #2 Volt= 60 Temp= 22 pH= 5.47		Jar #3 Volt= 62 Temp= 22 pH= 5.47		Jar #4 Volt= 62 Temp= 22 pH= 5.45	
	Time (s)	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*	*Time (s)*
	+	-	+	-	+	-	+	-	+	-
1	4.29	5.12	5.08	5.49	9.53	8.21	6.34	6.65	4.79	8.15
2	4.18	4.27	4.57	4.97	6.9	6.17	7.91	6.68	6.6	7.39
3	4.6	4.05	5.11	5.83	9.34	9.97	8.44	7.76	7.13	10.78
4	4.31	4.71	6.62	7.25	8.29	9.03	6.62	6.05	7.65	8.36
5	4.11	4.25	5.81	4.64	6.59	10.36	5.83	5.82	5.78	7.36
6	4.81	4.74	5.25	4.9	7.51	10.89	6.54	5.96	5.88	6.43
7	3.84	4.59	5.59	5.31					10.08	8.37
8										
9										
10										
Avg.	4.31	4.53	5.43	5.48	8.03	9.11	6.95	6.49	6.84	8.12
Avg Time (sec)	4.42		5.46		8.57		6.72		7.48	
Particles Charge Sign	-1		-1		1		1		1	
Velocity (um/sec)	13.58		10.99		7.00		8.93		8.02	
Field Strength (volt/cm)	10.03		10.03		10.03		10.36		10.36	
EPM (um/sec/volt/cm)	**-1.354**		**-1.096**		**0.698**		**0.862**		**0.774**	

V=60/Time
F.S.=Volt/5.983
EPM=V/F.S.

Flocculation Mixing-Natural Water

Optimization of coagulant

Experiment # 1

Coagulant Type: PACl

Coagulant Stock Solution Concentration (mg/L): 7.74×10^{3} as Al

Date: 1/22/96

Time: 9:30 AM

Parameter	Raw Water Before Spiking	Raw Water AfterSpiking	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)			0	5	25	45
Volume per 1 L (uL)			0	646	3230	5814
pH after adding PACl pH at end of exp.	7.67	7.50	7.50 7.77	7.20 7.43	6.48 6.98	6.07 6.6
Turbidity (NTU)	0.60	1.20	0.83	0.34	0.25	0.25
Filtered UV (cm-1)	0.107	0.110	0.095	0.079	0.048	0.047
Temperature (°C)	22	22	22	22	22	22
Particle Concentration(#/mL) Log N	4502 3.653	74319 4.871	71562 4.855	1917 3.283	2561 3.408	1928 3.285
EPM (um/sec/volt/cm)	-0.882	-1.320	-1.320	-1.000	N.R.	+
DOC mg/L C	5.30	5.81	-	-	3.11	-
Chlorophyll-a (ug/L)	0.175	17.826	17.826	0.000	0.000	0.000

Flocculation Mixing-Natural Water

Optimization of coagulant

Experiment # 2

Coagulant Type: PACl

Coagulant Stock Solution Concentration (mg/L): 7.74×10^{3} as Al

Date: 1/22/96

Time: 1:30 PM

Parameter	Raw Water Before Spiking	Raw Water AfterSpiking	Jar # 1	Jar # 2	Jar # 3	Jar # 4
Coagulant Dose (mg/L)			15	20	25	35
Volume per 1 L (mL)			1.948	2.584	3.247	4.522
pH after adding PACl pH at end of exp.	7.67	7.73	- 7.05	- 6.87	- 6.78	- 6.55
Turbidity (NTU)	0.60	1.40	0.34	0.27	0.24	0.29
Filtered UV (cm-1)	0.107	0.100	0.065	0.053	0.054	0.049
Temperature (°C)	22	22.2	22	22	22	22
Particle Concentration(#/mL) Log N	4502 3.653	81844 4.913	4974 3.697	2417 3.383	832 2.920	1510 3.179
EPM (um/sec/volt/cm)	-0.882	-1.320	-0.989	-0.544	-0.563	+
DOC mg/L C	5.30	6.60	4.34	2.25	1.84	1.73
Chlorophyll-a (ug/L)	0.175	19.793	0.063	0.000	0.000	0.000

Flocculation Mixing-Natural Water

Optimization of mixing intensity

Experiment #: 1
G=30 s^{-1} (N=60 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 25
PACl volume (ml) 3.247

Date: 1/23/96
Time: 8:30 AM

Parameter	Raw Water	Spiked Water	Jar # 1	Jar # 2	Jar # 3
pH	7.80	7.89	6.56	6.63	-
Turbidity (NTU)	0.62	0.86	0.22	0.25	0.20
Filtered UV (cm-1)	0.100	0.100	0.048	0.045	0.048
Temperature (°C)	21.8	21.8	21.8	21.8	21.8
Particle Concentration(#/mL)	3970	69412	-	1699	12036
Log N	3.599	4.840	-	3.230	4.080
DOC mg/L C	8.12	5.68	2.55	2.36	2.31
Chlorophyll-a (ug/L)	0.206	46.705	0.000	0.000	0.262

Flocculation Mixing-Natural Water

Optimization of mixing intensity

Experiment #: 2
G=60 s^{-1} (N=100 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 25
PACl volume (ml) 3.247

Date: 1/23/96
Time: 11:30 AM

Parameter	Raw Water	Spiked Water	Jar # 1	Jar # 2	Jar # 3
pH	7.80	7.82	-	-	-
Turbidity (NTU)	0.62	0.93	0.25	0.25	0.25
Filtered UV (cm-1)	0.100	0.097	0.045	0.045	0.045
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL)	3970	77897	702	1100	506
Log N	3.599	4.892	2.846	3.041	2.704
DOC mg/L C	8.12	5.28	2.09	1.79	1.88
Chlorophyll-a (ug/L)	0.206	45.837	0.000	0.000	0.000

Flocculation Mixing-Natural Water

Optimization of mixing intensity

Experiment #: 3
G=250 s^{-1} (N=300 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 25
PACl volume (ml) 3.247

Date: 1/23/96
Time: 1:30 PM

Parameter	Raw Water	Spiked Water	Jar # 1	Jar # 2	Jar # 3
pH	7.80	7.77	6.65	6.63	6.63
Turbidity (NTU)	0.62	1.10	0.21	0.22	0.20
Filtered UV (cm-1)	0.100	0.097	0.045	0.047	0.047
Temperature (°C)	22	22	22	22	22
Particle Concentration(#/mL)	3970	79531	631	640	381
Log N	3.599	4.901	2.800	2.806	2.581
DOC mg/L C	8.12	6.55	3.79	3.54	3.67
Chlorophyll-a (ug/L)	0.206	8.037	0.000	0.000	0.000

G, PSD, DAF Experiment

Experiment 1, Set 1

Experiment # 1

$G=30\ s^{-1}$ (N=60 rpm)

Coagulant Type: PACl

Optimum Dose (mg/L): 1.0

PACl volume (ul) 129

PACl stock soln. conc. (mg/L) 7.74×10^3

Date: 2/28/96

Parameter	Spiked Water	Jar # 1	Jar # 2
pH (pH after adjustment)	6.66	6.6	6.58
Turbidity (NTU)	0.86	0.21	0.25
Particle Concentration(#/mL) Log N	104209 5.018	246 2.391	224 2.350
Chlorophyll-a (ug/L)	19.56	0.40	0.30

Experiment 1, Set 2

Experiment # 2

$G=30\ s^{-1}$ (N=60 rpm)

Coagulant Type: PACl

Optimum Dose (mg/L): 1.0

PACl volume (ul) 129

PACl stock soln. conc. (mg/L) 7.74×10^3

Date: 2/29/96

Parameter	Spiked Water	Jar # 1	Jar # 2
pH (pH after adjustment)	6.81	6.63	6.6
Turbidity (NTU)	0.61	0.29	0.27
Particle Concentration(#/mL) Log N	76917 4.886	2252 3.353	2378 3.376
Chlorophyll-a (ug/L)	19.45	0.70	0.51

G, PSD, DAF Experiment
Experiment 2, Set 1

Experiment # 3
$G=60\ s^{-1}$ (N=100 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg/L) 7.74×10^3

Date: 2/28/96

Parameter	Spiked Water	Jar # 1	Jar # 2
pH (pH after adjustment)	6.75	6.54	6.57
Turbidity (NTU)	0.74	0.29	0.22
Particle Concentration(#/mL) Log N	97927 4.991	192 2.283	1167 3.067
Chlorophyll-a (ug/L)	19.21	0.17	0.33

Experiment 2, Set 2

Experiment # 4
$G=60\ s^{-1}$ (N=100 rpm)

Coagulant Type: PACl
Optimum Dose (mg/L): 1.0
PACl volume (ul) 129
PACl stock soln. conc. (mg/L) 7.74×10^3

Date: 3/1/96

Parameter	Spiked Water	Jar # 1	Jar # 2
pH (pH after adjustment)	6.93	6.37	6.32
Turbidity (NTU)	0.63	0.21	0.21
Particle Concentration(#/mL) Log N	86125 4.935	1145 3.059	1097 3.040
Chlorophyll-a (ug/L)	18.64	0.30	0.17

G, PSD, DAF Experiment

Experiment 3, Set 1

Experiment # 5

$G=250\ s^{-1}$ (N=300 rpm)

Coagulant Type: PACl

Optimum Dose (mg/L): 1.0

Date: 2/29/96

PACl volume (ul) 129

PACl stock soln. conc. (mg/L) 7.74×10^3

Parameter	Spiked Water	Jar # 1	Jar # 2
pH	6.71		
(pH after adjustment)		6.63	6.67
Turbidity (NTU)	0.83	0.25	0.24
Particle Concentration(#/mL)	131909	2172	3186
Log N	5.120	3.337	3.503
Chlorophyll-a (ug/L)	21.53	0.37	0.29

Experiment 3, Set 2

Experiment # 6

$G=250\ s^{-1}$ (N=300 rpm)

Coagulant Type: PACl

Optimum Dose (mg/L): 1.0

Date: 3/1/96

PACl volume (ul) 129

PACl stock soln. conc. (mg/L) 7.74×10^3

Parameter	Spiked Water	Jar # 1	Jar # 2
pH	6.65		
(pH after adjustment)		6.26	6.3
Turbidity (NTU)	0.60	0.18	0.20
Particle Concentration(#/mL)	82970	-	528
Log N	4.919	-	2.723
Chlorophyll-a (ug/L)	18.29	0.29	0.27

Change in % cumulative total number and volume over time

Exp. 1: 80 rpm

Size of particles	Number									Volume								
	Time (min)									Time (min)								
Time (min)	raw	0	1	3	5	7	9	10	20	raw	0	1	3	5	7	9	10	20
<2 um	28.35	12.26	8.91	7.41	6.55	3.53	3.19	3.33	0.68	0.49	0.21	0.15	0.13	0.11	0.06	0.05	0.03	0.01
2 to 4 um	47.66	19.26	16.27	13.37	11.34	6.11	7.01	7.69	0.87	22.16	8.96	7.57	6.22	5.27	2.84	3.26	3.58	0.41
4 to 6 um	18.94	8.06	7.21	6.43	5.46	3.37	4.06	4.14	0.22	40.77	17.35	15.52	13.85	11.75	7.25	8.75	8.92	0.48
6 to 8 um	4.26	4.27	3.92	3.82	3.23	2.45	3.01	2.84	0.05	25.14	25.22	23.18	22.55	19.09	14.47	17.77	16.78	0.31
8 to 10 um	0.77	3.55	3.37	3.76	3.62	3.866894	4.489171	3.99	0.02	9.63	44.52	42.29	47.18	45.46	48.55	56.36	50.05	0.26
10 to 15 um	0.01612	0.29	0.26	0.41	0.59	1.14	1.01	1.00	0.01	0.54	9.86	8.85	13.72	19.99	38.39	34.01	33.62	0.27
15 to 20 um	0.005226	0.04	0.04	0.06	0.13	0.33	0.24	0.28	0.00	0.48	3.97	3.85	5.69	11.70	30.52	21.91	26.03	0.27
20 to 25 um	0.004013	0.01	0.01	0.01	0.03	0.11	0.05	0.08	0.00	0.79	1.18	1.58	1.18	5.61	21.01	10.24	14.90	0.36

Exp. 2: 100 rpm

Size of particles	Number									Volume								
	Time (min)									Time (min)								
	raw	0	1	3	5	7	9	10	20	raw	0	1	3	5	7	9	10	20
<2 um	27.64	7.50	7.30	4.57	3.55	3.79	2.97	6.60	0.41	0.48	0.13	0.13	0.08	0.06	0.07	0.05	0.12	0.01
2 to 4 um	48.08	14.19	14.29	9.81	10.13	10.27	8.43	14.42	0.41	22.65	6.69	6.74	4.62	4.77	4.84	3.97	6.80	0.19
4 to 6 um	19.62	6.51	6.52	5.02	5.63	5.68	4.88	6.91	0.09	42.80	14.19	14.22	10.95	12.27	12.40	10.64	15.07	0.20
6 to 8 um	3.93	3.65	3.55	3.14	3.67	3.64	3.29	3.86	0.03	23.54	21.84	21.26	18.79	21.99	21.82	19.71	23.08	0.17
8 to 10 um	0.70	3.59	3.23	3.74	4.02	3.894269	4.047337	3.91	0.03	8.92	45.70	41.12	47.56	51.16	49.54	51.49	49.74	0.33
10 to 15 um	0.013447	0.38	0.34	0.66	0.59	0.59	0.75	0.57	0.01	0.46	13.10	11.71	22.59	20.11	19.96	25.64	19.42	0.28
15 to 20 um	0.00417	0.06	0.06	0.15	0.12	0.13	0.22	0.11	0.00	0.39	5.33	6.05	14.01	11.49	12.62	20.33	10.61	0.40
20 to 25 um	0.003763	0.02	0.02	0.04	0.03	0.05	0.09	0.03	0.00	0.75	3.32	3.93	7.22	6.63	9.23	17.33	6.84	0.70

Exp. 3: 300 rpm

Size of particles	Number									Volume								
	Time (min)									Time (min)								
	raw	0	1	3	5	7	9	10	20	raw	0	1	3	5	7	9	10	20
<2 um	28.52	6.09	5.36	4.16	3.42	3.42	4.07	4.96	0.41	0.46	0.10	0.09	0.07	0.06	0.06	0.07	0.08	0.01
2 to 4 um	45.74	10.67	9.82	8.24	7.18	7.15	8.26	9.97	0.49	20.00	4.66	4.29	3.60	3.14	3.13	3.61	4.36	0.21
4 to 6 um	20.20	4.72	4.74	4.40	3.93	4.03	4.46	5.35	0.28	40.91	9.56	9.59	8.92	7.96	8.16	9.03	10.84	0.56
6 to 8 um	4.53	2.63	2.73	2.82	2.61	2.77	2.88	3.34	0.17	25.14	14.64	15.17	15.66	14.48	15.39	15.99	18.54	0.92
8 to 10 um	0.97	2.45	2.82	3.34	3.14	3.425927	3.401478	3.65	0.22	11.43	28.88	33.27	39.43	37.06	40.45	40.16	43.05	2.62
10 to 15 um	0.033879	0.35	0.47	0.59	0.61	0.65	0.59	0.54	0.06	1.07	11.10	14.78	18.56	19.18	20.44	18.72	16.93	1.94
15 to 20 um	0.007155	0.10	0.12	0.13	0.17	0.16	0.14	0.09	0.02	0.62	8.53	10.47	10.98	14.75	13.76	11.76	7.90	1.45
20 to 25 um	0.001987	0.03	0.03	0.02	0.05	0.03	0.03	0.01	0.01	0.37	5.58	5.65	3.36	9.01	6.44	5.92	1.11	2.30

Change in Total Number and Volume Concentrations Over Time as a Percent of the Total Concentration in Raw Water

	Raw		t = 0 min		t = 1 min		t = 3 min		t = 5 min	
	Number	Volume	Number	Volume	Number	Volume	Number	Volume	Number	Volume
RPM	raw	raw	0 min	0 min	1 min	1 min	3 min	3 min	5 min	5 min
60	100.00	100.00	47.74	111.27	39.99	102.99	35.27	110.53	30.95	118.99
100	100.00	100.00	35.89	110.30	35.33	105.15	27.13	125.83	27.74	128.49
300	100.00	100.00	27.03	83.04	26.08	93.31	23.69	100.58	21.11	105.63

	t = 7 min		t = 9 min		t = 10 min		t = 20 min	
	Number	Volume	Number	Volume	Number	Volume	Number	Volume
RPM	7 min	7 min	9 min	9 min	10 min	10 min	20 min	20 min
60	20.90	163.08	23.06	152.35	23.35	153.93	1.86	2.38
100	28.06	130.49	24.67	149.17	36.41	131.67	0.98	2.27
300	21.64	107.82	23.82	105.26	27.90	102.80	1.78	10.02